# Ballot Draft # 6448

# Text highlighted in green reflects changes from the 1st edition

# Qualification of Metal Additive Manufacturing Processes for Use in the Petroleum and Natural Gas Industries

API STANDARD 20S

SECOND EDITION, XX XXX

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# 1 Scope

## 1.1 Purpose

This standard specifies requirements for qualification of the manufacturing process, production, marking, and documentation of additively manufactured metallic components used in the petroleum and natural gas industries when referenced by an applicable API equipment standard or otherwise specified as a requirement for conformance. The qualification process flowchart is shown in Figure 1.

## 1.2 Applicability

This standard applies to additively manufactured metallic components produced by powder bed fusion (PBF), directed energy deposition (DED), and binder jetting (BJT) processes.

## 1.3 Additive Manufacturing Specification Levels (AMSL)

This standard establishes requirements for three additive manufacturing specification levels (AMSL). These three AMSL designations—AMSL 1, AMSL 2, and AMSL 3—define increasing levels of additive manufacturing technical, quality, and qualification requirements.

NOTE An AMSL can be assigned to a component by a product specification or standard, the purchaser, or the manufacturer.

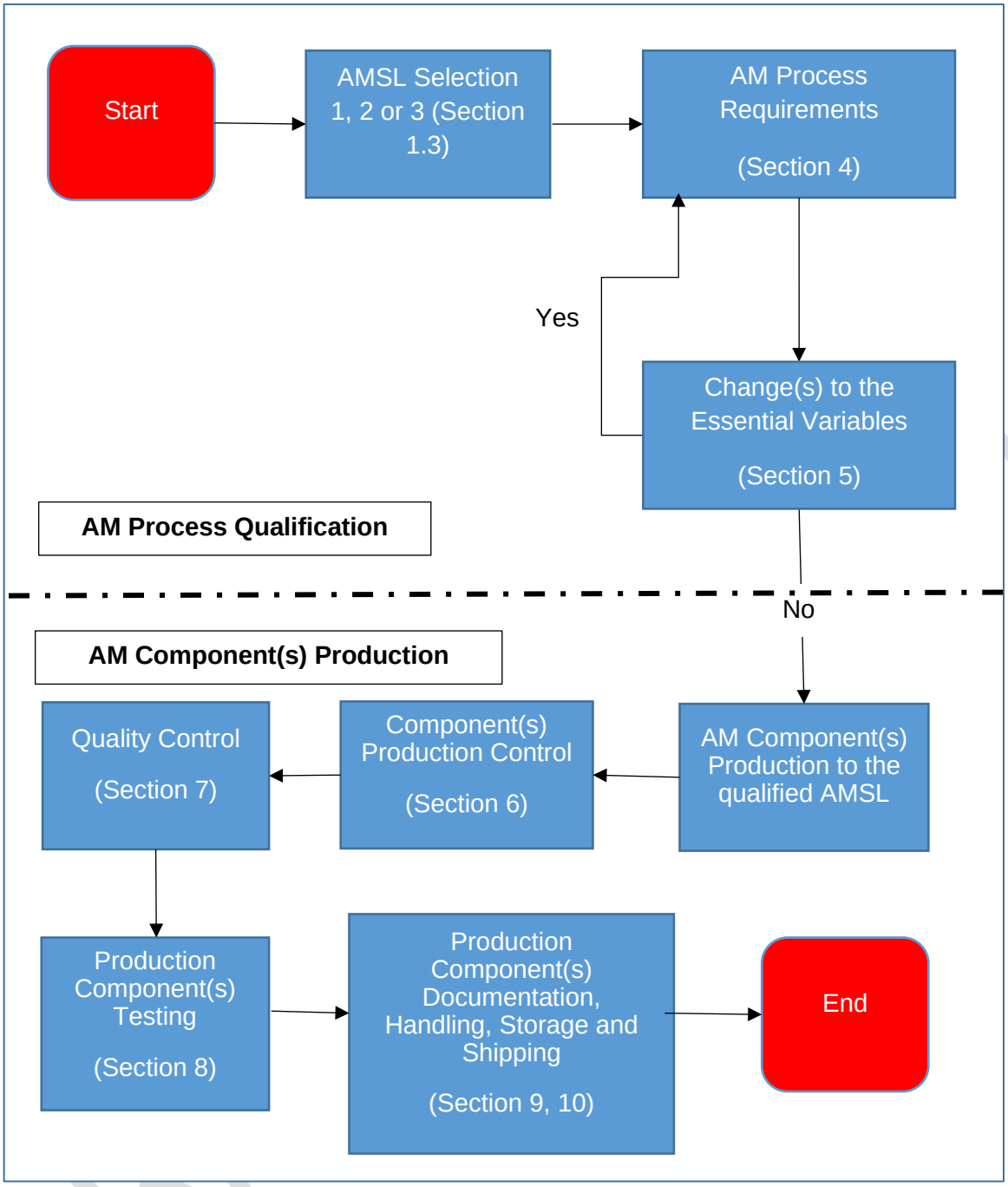


**Figure 1—Qualification Process Flowchart**

## 2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

*API Specification Q1, Specification for Quality Management System Requirements for Manufacturing Organizations for the Petroleum and Natural Gas Industry*

*API 6A, Specification for Wellhead and Tree Equipment*

*ANSI1/ASQ Z1.4,2 Sampling Procedures and Tables for Inspection by Attributes*

*ASME BPVC, Section IX - Welding, Brazing and Fusing Qualifications*

*ASTM A370, Standard Test Methods and Definitions for Mechanical Testing of Steel Products*

*ASME3 BPVC, Section II—Materials, Part C—Specifications for Welding Rods, Electrodes, and Filler Metals*

*ASTM4 B294, Standard Test Method for Hardness Testing of Cemented Carbides</std>*

*ASTM B311, Standard Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity*

*ASTM B406, Standard Test Method for Transverse Rupture Strength of Cemented Carbides*

*ASTM B611, Standard Test Method for Determining the High Stress Abrasion Resistance of Hard Materials*

*ASTM B771, Standard Test Method for Short Rod Fracture Toughness of Cemented Carbides*

*ASTM B962, Standard Test Methods for Density of Compacted or Sintered Powder Metallurgy (PM) Products Using Archimedes' Principle*

*ASTM E8, Standard Test Methods for Tension Testing of Metallic Materials*

*ASTM E9, Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature*

*ASTM E10, Standard Test Method for Brinell Hardness of Metallic Materials*

*ASTM E18, Standard Test Methods for Rockwell Hardness of Metallic Materials*

*ASTM E23, Standard Test Methods for Notched Bar Impact Testing of Metallic Materials*

*ASTM E29, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications</std>*

*ASTM E92, Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials*



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[1] American National Standards Institute, 1899 L Street, NW, Washington, DC 20036, www.ansi.org.

[2] American Society for Quality, 600 North Plankinton Avenue, Milwaukee, Wisconsin 53203, www.asq.org.

[3] American Society of Mechanical Engineers, Two Park Avenue, New York, NY 10016, www.asme.org.

[4] ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org.

*ASTM E140, Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, Scleroscope Hardness, and Leeb Hardness*

*ASTM E228, Standard Test Method for Linear Thermal Expansion of Solid Materials with a Push-Rod Dilatometer*

*ASTM E384, Standard Test Method for Microindentation Hardness of Materials*

*ASTM E1461, Standard Test Method for Thermal Diffusivity by the Flash Method*

*ASTM G65, Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus*

*ASNT5 SNT-TC-1A, Personnel Qualification and Certification in Nondestructive Testing*

*EN6 10204, Metallic products — Types of inspection documents*

*ISO7 148-1, Metallic materials — Charpy pendulum impact test — Part 1: Test method*

*ISO 6506, Metallic materials — Brinell hardness test (parts 1 through 4)*

*ISO 6507, parts 1 through 4, Metallic materials — Vickers hardness test (parts 1 through 4)*

*ISO 6508, parts 1 through 3, Metallic materials — Rockwell hardness test (parts 1 through 3)*

*ISO 6892-1, Metallic materials — Tensile testing — Part 1: Method of test at room temperature*

*SO 9001, Quality management systems — Requirements*

*SO 9712, Non-destructive testing — Qualification and certification of NDT personnel*

*>ISO 18265, Metallic materials — Conversion of hardness values*

*ISO 28079, Hardmetals — Palmqvist toughness test*

*ISO/ASTM 52900, Additive manufacturing — General principles — Terminology*

*ISO/ASTM 52921, Standard Terminology for Additive Manufacturing — Coordinate Systems and Test Methodologies*

*ISO 80000-1, Quantities and units — Part 1: General*



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[5] American Society for Nondestructive Testing, PO Box 28518, 1711 Arlingate Lane, Columbus, Ohio 43228, www.asnt.org.

[6] European Committee for Standardization, Rue de la Science 23, B – 1040 Brussels, Belgium, www.cen.eu.

[7] International Organization for Standardization, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, www.iso.org.

# 3 Terms, Definitions, Acronyms, and Abbreviations

## 3.1 Terms and Definitions

For the purposes of this document, the terms and definitions given in ISO/ASTM 52900 and the following apply. Where identical terms and definitions are given, the terms and definitions provided in this specification supersede the terms and definitions contained in ISO/ASTM 52900.

**3.1.1**
**acceptance number**
The acceptance number is the maximum number of defects or defective units in the sample that will permit acceptance lot or batch.
**3.1.2**
**binder**
Liquid bonding agent or glue used in the binder jetting process for holding metal particles together.
**3.1.3**
**bracketed qualification**
See ASME BPVC, Section IX - Welding, Brazing and Fusing Qualifications
**3.1.4**
**build**
See “build cycle” in ISO/ASTM 52900.
**3.1.5**
**by agreement**
Agreed between manufacturer and purchaser.
**3.1.6**
**certificate of conformance**
A document containing the statement by the additive manufacturer certifying that the component(s) meets the requirements of this standard.
**3.1.7**
**cleaner**
A liquid cleaning agent used in the binder jetting process to maintain the quality of the print head jets (removing excess binder).
**3.1.8**
**component build file**
A file that defines the geometry, arrangement of the components, test specimens, and support structures, as applicable, that will be built by a piece of printing equipment. This file will be converted to build instructions.
**3.1.9**
**final condition**

Condition of the component as per design definition provided either in component specification or finished component engineering drawing/specification, including all thermal treatments necessary to achieve desired material properties but may exclude surface treatments such as coatings or painting.

**3.1.10**
**first article component**
A component that is manufactured with a manufacturing process to be qualified to this Standard.
**3.1.11**
**first article inspection**

A process of inspection in which a manufacturing process is validated to ensure compliance with this Standard.

**3.1.12**
**hard metal**
Material manufactured with binder jetting that typically combines a softer metallic phase and harder ceramic phase to create a harder wear-resistant material. The harder phase can either be incorporated in the green stage or introduced in situ.

**3.1.13**
**temperature Measurement Method, Inter-bead**
Temperature is measured and controlled prior to the start of each stringer bead or weave bead. Weld beads do not self-overlap without measurement of temperature.

**3.1.14**
**temperature Measurement Method, Inter-layer**
Temperature is measured and controlled prior to the start of each layer.

**3.1.15**
**live setter**
A setter made from the same material as the finished part.
**3.1.16**
**metallic**
A material that contains metal elements as the majority of the composition (by weight or by atomic percentage).
**3.1.17**
**on-site**
The additive manufacturer's facility.
**3.1.18**
**additive Manufacturing equipment**
See "AM Machine"' in ISO/ASTM 52900.
**3.1.19**
**procedure**
An organization's documented method for performing an activity under controlled conditions to achieve conformity to specified requirements.
**3.1.20**
**process consumables**
Material inputs to the additive manufacturing process that are specified in accordance with the component being manufactured (e.g., feedstock, binder, substrate, gas) as applicable to the process used.
**3.1.21**
**production component**
A component that is manufactured with a manufacturing process qualified to this standard.
**3.1.22**
**production lot**
All components of the same build with the same thermal post-processing.
**3.1.23**
**removable components**
Items that are removed or replaced as part of the manufacturing process (e.g., build plate, recoater blade).
**3.1.24**
**scaling strategy**

Adjusting the component size by a percentage in the x, y, and z dimensions of a part to accommodate the anisotropic effects in printing that occur during the sintering of the material in the binder jetting process.

**3.1.25**
**serviceable components**
Items that are removed/replaced/cleaned as part of a maintenance event (e.g., filters, lenses, laser).

**3.1.26**
**setter**
A fixture used in the furnace to control unwanted distortion caused by gravity of the part during sintering.

**3.1.27**
**substrate**
The surface onto which the initial layer of feedstock is deposited. This may be a build platform (e.g., for powder bed fusion), a surface that becomes an integral portion of the component, or a surface of an existing component (e.g., for DED).

**3.1.28**
**unused powder**
powder that has not yet been exposed to the conditions of the building chamber during the build process.

## 3.2 Acronyms and Abbreviations

For purposes of this standard, the following abbreviations apply.

AM additive manufacturing
AMF additive manufacturing file format
AMSL additive manufacturing specification level
BJT binder jetting
CAD computer-aided design
CT computed tomography
CVN Charpy V-notch
DED directed energy deposition
DPD digital product definition
EB electron beam
FMECA failure mode effects and criticality analysis
HIP hot isostatic pressing
IGES initial graphics exchange specification
LB laser beam
NDE nondestructive examination
MPS manufacturing process specification
OEM original equipment manufacturer
PBF powder bed fusion
PSD particle size distribution
QMS quality management system
STEP standard for the exchange of product model data
STL standard triangle language
3MF 3-D manufacturing format

# 4 Requirements for the Additive Manufacturing Process

## 4.1 General

This standard gives the requirements for three additive manufacturing specification levels (AMSL). The AMSLs are numbered in increasing levels of severity from 1 to 3 to reflect increasing technical, quality, and qualification criteria. This section describes the conditions that, when met, allow the additive manufacturing process to receive the appropriate AMSL classification.

When additively manufactured metallic components are ordered to an API product specification or API product standard, the API product specification or API product standard shall take precedence over this standard as long as the requirements of the API product specification or API product standard meet or exceed the minimum requirements set forth in this standard.

## 4.2 Additive Manufacturer Requirements

### 4.2.1 General

For all AMSLs, the additive manufacturer shall implement and maintain required controls to ensure products and services meet specified requirements and shall conform with the requirements of 4.2 and its subsections.

### 4.2.2 Additive Manufacturer Quality Management System (QMS)

The additive manufacturer shall establish, document, implement, and maintain, at all times, a QMS and associated processes. The QMS shall be in conformance with either API Q1 or ISO 9001.

### 4.2.3 Quality Control Procedures

**4.2.3.1** All quality control activities shall be controlled by the additive manufacturer's documented procedures, which include appropriate methodology and acceptance criteria.

**4.2.3.2**The additive manufacturer shall include a software/firmware update plan within the QMS. This plan shall contain methods of evaluating potential software updates applied to the AM machine or any major subsystems of the AM machine. Evaluations of any software updates shall be maintained as records. Where software/firmware updates are made without evaluation, or where evaluation cannot be performed, requalification shall be performed in accordance with 4.6 for the applicable AMSL level.

**4.2.3.3** NDE procedures shall be detailed regarding the requirements of all applicable nationally or internationally recognized standards specified by the additive manufacturer. All NDE procedures shall be approved by a Level III examiner qualified in accordance with ASNT SNT-TC-1A or ISO 9712 in the specified discipline.

### 4.2.4 Technical Review Requirements

The additive manufacturer shall maintain procedure(s) to ensure that technical requirements are reviewed prior to acceptance of the order.

The additive manufacturer shall maintain records of this review, including:

a) applicable purchaser or governing design and/or construction specifications/standards;

b) deviations from governing design and/or construction specifications/standards;

c) material specifications;

d) acceptance criteria;

e) qualification of procedures;

f) qualification of personnel;

g) qualification of printing equipment;

h) outsourced services;

i) inspection and testing requirements, including third-party verification;

j) identification and traceability;

k) post-processing requirements.

### 4.2.5 Personnel Training and Competency Requirements

Personnel shall be competent to carry out assigned tasks and responsibilities based on the appropriate education, training, skills, and experience needed to meet product and purchase order requirements. The additive manufacturer shall maintain a written procedure that defines personnel competency and identifies training and qualification requirements.

The additive manufacturer shall identify:

a) knowledge and training necessary to address specific requirements;

b) qualifications required for personnel performing processes that require validation;

c) method(s) used to verify the competency of personnel.

The additive manufacturer shall maintain evidence of conformity to the above requirements.

### 4.2.6 Non-destructive Examination Personnel Requirements

Personnel performing NDE shall be qualified in accordance with the additive manufacturer's documented training program that is based on the requirements specified in the following:

a) ISO 9712; or

b) ASNT SNT-TC-1A; or

c) a national or international standard that is equivalent to ISO 9712 or ASNT SNT-TC-1A.

NDE Level I or Level II personnel shall be qualified by NDE Level III personnel in the specified discipline.

### 4.2.7 Inspection Personnel Requirements

Personnel performing visual inspection for acceptance shall take and pass an annual vision examination in accordance with the additive manufacturer's documented procedure that is based on the requirements specified in the following:

a) ISO 9712; or

b) ASNT SNT-TC-1A; or

c) a national or international standard that is equivalent to ISO 9712 or ASNT SNT-TC-1A.

### 4.2.8 Other Personnel Requirements

All other personnel performing measurements, inspections, or tests for acceptance shall be qualified in accordance with the additive manufacturer's documented procedures and requirements.

#### 4.2.9 Facility Requirements

The additive manufacturer shall have on-site equipment and personnel to perform the required processes needed to produce the components under the scope of this standard as identified below:

a) equipment to perform required printing activities (excluding post-processing activities);

b) storage and usage of the process consumables and equipment in accordance with the requirements of this standard;

c) appropriate handling and lifting equipment (as applicable);

d) inspection and test equipment (as applicable).

#### 4.2.10 Monitoring and Measuring Equipment Requirements

Instruments used to measure and control critical process variables during the additive manufacturing process, including all post-processing activities, shall be serviced and calibrated in accordance with written specifications.

Equipment used to inspect, test, or examine material or other equipment shall be identified, controlled, calibrated, and adjusted at specified intervals in accordance with documented instructions, and consistent with nationally or internationally recognized standards, to maintain the accuracy required by this standard.

### 4.3 Feedstock Requirements

#### 4.3.1 Feedstock Suppliers

The feedstock supplier shall maintain a quality management system that, at a minimum, conforms to ISO 9001.

#### 4.3.2 Feedstock Material

##### 4.3.2.1 General

The additive manufacturer shall maintain feedstock specifications that include, at a minimum, the requirements listed in the subsections below.

##### 4.3.2.2 Powder Feedstock

Unused powder feedstock requirements shall be defined by powder specifications. Testing methodologies shall be defined and in accordance with internationally recognized standards or specifications (e.g., ISO/ASTM 52907). At a minimum, the feedstock specification shall address:

a) alloy and/or grade designation;

b) chemical composition;
c) particle size distribution;
d) density;
e) flow properties;
f) method of powder manufacture;
g) storage, preservation, and handling requirements;
h) certification requirements.

#### 4.3.2.3 Wire Feedstock

Wire feedstock shall conform to a classification in ASME BPVC, Section II, Part C and shall be certified according to Table 1.

**Table 1 - Wire Feedstock Requirements**

| AMSL | Lot Classification per AWS A5.01 | Level of Testing per AWS A5.01 |
|---|---|---|
| 1 | S1 or T1 | Schedule F |
| 2 | S3 or S4 or T3 or T4 | Schedule H |
| 3 | S3 or S4 or T3 or T4 | Schedule H |

#### 4.3.2.4 Binder Feedstock

Unused binder feedstock requirements, including testing methodologies, shall be defined by binder specifications. At a minimum, the binder specification shall address:

a) grade;
b) composition ranges;
c) storage, preservation, and handling requirements;
d) viscosity;
e) surface tension;
f) thermogravimetric analysis profile;
g) flash point;
h) evaporation temperature;
i) curing temperature;
j) expiration date, if applicable.

#### 4.3.2.5 Cleaner Feedstock

Cleaner feedstock requirements, including testing methodologies, shall be defined by cleaner specifications. At a minimum, the cleaner specification shall address:

a) grade;
b) storage, preservation, and handling requirements;
c) composition ranges;
d) expiration date, if applicable.

### 4.3.3 Feedstock Storage

The additive manufacturer shall maintain a documented procedure for storage and handling of feedstock.

Feedstock shall be stored and packaged to prevent moisture adsorption and contamination.

### 4.3.4 Powder Reuse

The additive manufacturer shall maintain a documented procedure for powder reuse, including, at a minimum:

a) end-of-life processing for the feedstock powder;
b) reclaiming powder;
c) characterizing any reclaimed powder for reuse;
d) minimizing contamination and oxygen pickup during powder reuse.

### 4.3.5 Binder Reuse

For binder jetting, the additive manufacturer shall maintain a documented procedure for reuse binder (i.e., blending used binder with unused binder) and monitoring green, printed component characteristics, including steps to minimize contamination.

### 4.3.6 Feedstock Change Plan

The additive manufacturer shall maintain a procedure(s) to address the change of feedstock in printing equipment.

When replacing powder and binder feedstock with that of matching specification, a nominal cleaning of the AM equipment (i.e., tools, sieving stations, etc.) is required. When replacing powder and binder feedstock with that of a different specification (particularly with that of a differing chemistry), a thorough/deep cleaning of AM equipment including all powder-contacting surfaces of the AM equipment shall be performed.

### 4.3.7 Powder and Binder Feedstock AMSL Requirements

#### 4.3.7.1 Powder and Binder Feedstock AMSL 1 Requirements

**4.3.7.1.1** For powder, the consumable certification shall include the batch number, grade, production method, nominal particle size distribution, and nominal composition.

**4.3.7.1.2** For binder feedstock and cleaner feedstock, consumable certification shall include grade names.

**4.3.7.1.3** The manufacturer shall ensure that powder certificate of conformance is compliant to powder specification for every new batch of powder received.

#### 4.3.7.2 Powder and Binder Feedstock AMSL 2 Requirements

In addition to the AMSL 1 requirements, the following applies:

a) For PBF, the additive manufacturer shall maintain a documented procedure for powder sampling and periodic testing to determine that PSD, morphology, and flow rate are within specification limits.

b) For powder, the certification shall include the apparent density and the shape as defined by representative micrographs or alternate measurement techniques.

c) There are no additional requirements for binder.

#### 4.3.7.3 Powder and Binder Feedstock AMSL 3 Requirements

For powder, in addition to AMSL 2 requirements, unused powder is required. By agreement, blended powder may be used provided that powder samples representative of the powder batch are collected and analyzed to determine PSD, morphology, flowrate, and chemistry are within specification limits.

For binder feedstock and cleaner feedstock, in addition to AMSL 2 requirements, the additive manufacturer shall use only unused binder feedstock and unused cleaner feedstock.

## 4.4 Substrate Requirements

### 4.4.1 General

If a substrate is used, the additive manufacturer shall define a substrate specification that, at a minimum, includes:

a) compatibility of the substrate material grade with the feedstock grade and any shielding gases used;

b) geometrical requirements, including minimum thickness, XY dimensions, parallelism, and tolerance requirements;

c) Required surface preparation (e.g. roughness, cleaning, etc.).

### 4.4.2 Integrated Substrates

When the substrate is integrated within the final component, the additive manufacturer shall confirm that the mechanical and metallurgical properties at the interface between the substrate and the deposited material are

in accordance with the requirements of the applicable material specification, product specification, and manufacturing process specification (MPS).

The substrate used for the qualification shall be representative of the substrate used in production; for example, if the initial layer is to be deposited onto forged material, the qualification is performed using a forged substrate.

## 4.5 Additive Manufacturing Equipment

### 4.5.1 General

The additive manufacturer shall maintain additive manufacturing equipment qualification procedures that address qualification requirements and the following as applicable:

a) installation, operation, and maintenance requirements;

NOTE The change of the AM equipment physical location should take into account the effect of environmental factors (e.g., humidity) when using previously qualified DPD files for manufacture of production components.

b) qualification geometry(s) and associated test plan (including acceptance criteria) that incorporate overlap areas in systems with multiple energy sources;

c) essential variables as defined in Section 5;

d) substrate surface preparation, including cleaning method, positioning, and clamping;

e) curing oven;

f) de-powdering equipment;

g) powder reuse equipment;

h) sintering furnace;

i) modifications to the print head or shielding gas hardware configuration for DED processes.

NOTE For DED wire arc welding systems, some of these requirements may be addressed by reference to a welding quality system, such as the ISO 3834 series of standards.

### 4.5.2 Preventative Maintenance Plan

For all AMSLs, the additive manufacturer shall maintain a preventative maintenance plan that covers the AM printing equipment, including a schedule that addresses the following as applicable:

a) climate control requirements (e.g., temperature and humidity) and recorded history;

b) gas supply system requirements, where used, that shall be in accordance with the AM printing equipment manufacturer instructions (e.g., for pressure, temperature, flow rate, cleanliness);

c) power supply requirements, which are defined and verified during installation and ongoing servicing (e.g., installation certificate and service reports);

d) instructions for the cleaning of the AM printing equipment, associated tools, and auxiliary equipment;

e) cleaning/purging and inspection requirements for the AM printing equipment (including frequency of cleaning and definition of events that would require cleaning to be performed, such as a material changeover from one feedstock material grade to another);

f) requirements for the maintenance and inspection of serviceable and removable components;

g) calibration requirements and calibration record history shall be maintained for printing and auxiliary equipment, as applicable; for binder jetting, the auxiliary equipment includes the curing oven and sintering furnace.

Non-contaminating cleaning solutions for the equipment shall be used.

NOTE For DED wire arc welding systems, some of these requirements may be addressed by reference to a welding quality system, such as the ISO 3834 series of standards, or accreditation by AWS as a Certified Welding Facility.

#### 4.5.3 Qualification Records

Additive manufacturing equipment qualification records shall include:

a) additive manufacturer facility name and address;

b) additive manufacturing equipment manufacturer and model (PBF and BJT only);

c) additive manufacturing equipment unique system identifier, such as serial number

d) software and firmware versions;

e) operator qualification record number;

f) qualifying test build records, including geometry, photographic, or diagrammatic record of test specimen locations when machined from a larger test build, indication of the approved build area. For multi-energy source machines, the test records in all overlapping regions, values of the essential variables, as defined in Section 5, and test results.

g) curing oven (BJT only);

h) sintering furnace (BJT only).

### 4.6 First Article Component

The first article component is used to qualify the entire manufacturing process.

#### 4.6.1 General

The first article component shall be manufactured with the same MPS as the production components in accordance with Section 6.2.

#### 4.6.2 Digital Product Definition File

**4.6.2.1** The digital product definition (DPD) file collects all the data required to reproduce an additively manufactured metallic component.

**4.6.2.2** The additive manufacturer shall have a documented procedure to develop and maintain the DPD file, which includes the digital data required to additively manufacture the component. At a minimum, the DPD file shall include, as applicable:

a) geometry: component CAD files (e.g., STL, AMF, 3MF, STEP, IGES);

b) component build file;

c) all files that control the behavior of the slicing or build preparation software;

d) printing strategy (e.g., laser focus, laser spot size etc.), including compatibility with selected substrate, as applicable;

e) all printing equipment settings and instructions not included in the build file;

f) software used: a record of all versions of all software used to produce the files listed above;

g) build heating and cooling strategy (alternatively, the heating and cooling strategy can be addressed in the MPS; see 6.2. For example, this may include water cooling of the build platform in the case of DED, or active heating of the build platform or chamber for PBF and EB);

h) for BJT, a record of the material, geometry, and position of the setters and/or live setters during sintering;

i) for DED-wire AMSL 2 and AMSL 3, a qualified welding procedure and a temperature control plan (e.g. temperature measurement method, frequency, hardware type).

**4.6.2.3** The additive manufacturer shall have a procedure to ensure the integrity of the DPD file and shall maintain records of the revision history of the DPD.

### 4.6.3 First Article Inspection Quality Control Requirements

**4.6.3.1** The first article component shall be manufactured in accordance with the same DPD and MPS to be used for manufacture of production component(s). When using a DPD that contains multiple components, one first article component shall be selected randomly from each group of components of the same geometry, unless otherwise agreed.

**4.6.3.2** First article inspection and testing shall be performed as specified in Table 2, Table 3, Table 4, and Table 5. Orientations referred to in these tables are as defined in ISO/ASTM 52921.

**4.6.3.3** Where multiple energy sources are used in a build, the test coupons should be arranged to ensure that the material properties of the areas affected by different energy sources and any overlapping regions are captured. In addition, in all the overlapping regions, test coupons shall be arranged to demonstrate beam alignment.

NOTE PBF printing equipment manufacturers typically have their own specific test specimen/coupons to test the machine performance in the lasers overlapping regions.

#### 4.6.3.1 AMSL 1 and AMSL 2 First Article Inspection Quality Control Requirements

**4.6.3.1.1** The destructive testing to assess the first article component material properties shall be performed by using test specimens extracted and machined from prolongations or printed concurrently. The test specimens shall be co-located in the build with the first article component on the same build platform and shall be subjected to the same thermal-post-production processing. For BJT, this shall also include post-printing steps (curing, de-powdering, and sintering).

**4.6.3.1.2** For DED-wire processes, AMSL 1 first article testing shall use a qualified weld procedure, and additional testing shall be performed as specified in Table 3.

**4.6.3.1.3** For DED-wire processes AMSL 2 first article testing shall use a qualified welding procedure as defined in Section 5.2, additional testing shall be performed as specified in Table 3 and the test coupons shall be considered as the first article. The production component DPD and the MPS shall reference all qualified procedures used in first article testing.

#### 4.6.3.2 AMSL 3 First Article Inspection Quality Control Requirement

**4.6.3.2.1** The first article component shall be used as a sacrificial component to extract test specimen(s). By agreement, the properties of the first article component may be assessed by using specimen(s) as described for AMSL 1 and AMSL 2If concurrently printed specimens are to be used for an AMSL 3 PBF component, the gauge length of the specimen(s) in the Z-orientation and the planes of microstructure analysis shall encompass the Z-height of the critical section(s) of the component such as those identified by the stress distribution in the design documentation. If geometry limitations prevent specimens from being manufactured concurrently at the appropriate Z-height, the test specimen height shall be by agreement.

NOTE: Design of the build plate should include considerations for specific placement of the purposefully printed test specimens that is dependent on the build plate size and number of components printed concurrently with the specimens, as the intent is to produce specimens that approximate the same thermal history as the first article component.

**4.6.3.2.2** For DED-wire processes AMSL 3 first article testing shall use a qualified welding procedure as defined in Section 5.2 and additional testing shall be performed as specified in Table 3.

**4.6.3.2.3** By agreement, for DED processes, the printed geometry of the first article component DPD may be different than the production component DPD provided that the design is representative of the production component. The printed geometry should consider, for example, print orientation(s), feature(s), thickness(es), and path strategies. The MPS shall reference all DPDs used in the first article component build. When separate DPD(s) are used, test specimens shall be produced immediately before or after the first article component.

NOTE Different and/or multiple geometries may be required to obtain the required test specimens for material testing in accordance with 4.6.4 or to reduce the amount of material (size) required for evaluation.

### 4.6.4 Material Testing

#### 4.6.4.1 General

All material tests shall be performed after thermal post-processing steps have been performed, as these can affect material properties. The methods used and corresponding acceptance criteria shall be as stated in the applicable material specification, product specification, and/or MPS. In the absence of a specified procedure for rounding within the applicable test method, an observed or calculated value shall be rounded to the nearest unit in the last right-hand place of figures used in expressing the limiting values for other quantities in accordance with the rounding-off method given in ASTM E29 or ISO 80000-1.

NOTE In some instances, it may be prudent to subject the test specimens not only to the thermal treatment, but to any additional post-fabrication steps imparted to the first article component that could impact the material properties.

#### 4.6.4.2 Chemical Analysis

Chemical analysis shall be performed using a suitable method in accordance with a nationally or internationally recognized standard. The methods selected shall be capable of detecting and quantifying all elements specified in the relevant design and material standards.

Acceptance criteria shall be in accordance with the relevant design and material standards as stated in the MPS and/or applicable API product specification or API product standard.

#### 4.6.4.3 Tensile Testing

**4.6.4.3.1** Tensile tests shall be performed in accordance with the procedures specified in ASTM A370, ASTM E8, or ISO 6892-1 and the following parameters shall be reported, as applicable:

a) yield strength;

b) ultimate tensile strength;

c) elongation;

d) reduction of area.

**4.6.4.3.2** Acceptance criteria shall be in accordance with the relevant design and material standards as stated in the MPS and/or applicable API product specification or API product standard.

**4.6.4.3.3** If the results of the tensile test(s) do not satisfy the applicable requirements, two additional tests on tensile specimens removed from the required location in the same build and in the same orientation with no additional heat treatment may be performed to qualify the material, and the results of each of these tests shall satisfy the applicable requirements.

For BJT, tensile testing is not required for hard metals; see Annex C for guidance.

#### 4.6.4.4 Impact Testing

**4.6.4.4.1** CVN impact tests shall be conducted as specified in ASTM A370, ASTM E23, or ISO 148-1.

**4.6.4.4.2** For the purpose of determining conformance with these requirements, the observed result of a test shall be rounded to the nearest whole number. The impact energy value for a set of test specimens (i.e., average of three tests) shall be as a whole number, rounded if necessary.

**4.6.4.4.3** Acceptance criteria and test temperature shall be in accordance with relevant design and material specification(s) as stated in the MPS and/or applicable API product specification or API product standard. If a test fails, a retest of three additional specimens removed from the required location in the same build and in the same orientation, with no additional heat treatment, may be made, each of which shall exhibit an impact value equal to or exceeding the required minimum average value.

For BJT, impact testing is not required for hard metals; see Annex C for guidance.

#### 4.6.4.5 Hardness Testing

**4.6.4.5.1** Except for hard metal components manufactured with BJT, hardness testing shall be performed in accordance with applicable procedures specified in ISO 6506 (parts 1 through 4), ASTM E10 (Brinell), ISO

6508, (parts 1 through 3), ASTM E18 (Rockwell), ISO 6507 (parts 1 through 4), or ASTM E92 or ASTM E384 (Vickers). A specific hardness test method shall be selected based on requirements of relevant material or product specifications.

**4.6.4.5.2** For hard metal components manufactured with BJT, hardness testing shall be performed in accordance with applicable procedures.

EXAMPLE — Cemented carbide hardness testing should be performed in accordance with applicable procedures specified in ASTM B294.

NOTE 1 ISO 18265 or ASTM E140 may be used for the conversion of hardness readings for materials within the scope of their application.

**4.6.4.5.3** Acceptance criteria shall be in accordance with relevant design and material specifications as stated in the MPS and/or applicable API product specification or API product standard.

NOTE 2 Two types of hardness tests are used in these standards:

a) external surface tests involving a single indentation; and
b) cross-section hardness tests involving multiple indentations.

**4.6.4.5.4** When required by the applicable MPS, a cross-section hardness profile shall be determined by the Rockwell or Vickers method and used for product acceptance.

**4.6.4.5.5** In case of failure to meet the required hardness requirements, for Rockwell and Vickers, three additional indentations shall be made in the immediate area to determine new hardness values. If one or more of the re-test indentations do not meet hardness requirements, it shall be reported as non-conforming.

### 4.6.4.6 Microstructure Analysis

**4.6.4.6.1** Microstructure analysis shall be performed after the final thermal processing step. The plane of all photomicrographs shall be as listed in Table 2, Table 3, Table 4, or Table 5 for the applicable AMSL. The location and orientation of the photomicrographs within the build shall be reported.

**4.6.4.6.2** A minimum of four photomicrographs per orientation shall be provided. A first set of two photomicrographs shall include one photomicrograph of the as-polished, un-etched specimen, and a second one of a specimen etched with the appropriate reagent(s). The magnification of this first set of photomicrographs shall be approximately 100x; an additional set of two photomicrographs, as described above, shall be provided at 400x or greater. When required by the applicable material specification, product specification and/or MPS grain size shall be measured and reported.

**4.6.4.6.3** The measurement of material anomalies and voids shall be carried out using optical image analysis method on as polished (no chemical etching) specimens at a minimum magnification of 50x on an inspection area of ≥1 mm². The measurements shall be carried out in Z orientation as well as in 90° to the Z orientation. For binder jetting, only one orientation measurement is required. The % area of voids/porosity shall be reported along with the size of largest void observed in the field of view.

**4.6.4.6.4** The acceptance criteria shall be in accordance with relevant design and material specification as stated in the MPS and/or applicable API product specification or API product standard.

NOTE Microstructure analysis from tested CVN or tensile specimens is permitted, but should be taken from the undeformed portions of the test specimens.

### 4.6.4.7 Density Testing

Density measurement of a representative coupon or prolongation, built and processed alongside the first article component, shall be performed after the final thermal processing step. Measurement and reporting shall be according to ASTM B311, ASTM B962, or other equivalent method.

The acceptance criteria shall be in accordance with the relevant design and material specification as stated in the MPS and/or applicable API product specification or API product standard.

NOTE Alternative methods for measuring density, such as serial sectioning, may be considered based on component geometry and practicality. In general, these methods are more accurate than testing to the Archimedes principle and may be accepted. The micrographic examination sample may be considered for serial sectioning testing.

### 4.6.5 Non-destructive Examinations

Guidance on selection and application of NDE for AM components is provided in Annex D.

#### 4.6.5.1 Visual Inspection

Visual inspection acceptance criteria shall be in accordance with the applicable product specification or standard. Visual inspection of finished components shall be performed in accordance with the additive manufacturer's written specifications.

#### 4.6.5.2 Surface NDE

If required by the relevant design and material specifications as stated in the MPS and/or applicable API product specification or API product standard, all accessible surfaces of the component shall be examined by liquid-penetrant or wet fluorescent magnetic-particle methods after final machining and all thermal processing is completed. Surface NDE methods shall be in accordance with the applicable material specification and/or API product specification.

#### 4.6.5.3 Volumetric NDE

**4.6.5.3.1** The entire volume of the component shall be volumetrically inspected after completion of thermal post-processing, and prior to machining operations that limit effective interpretation of the results of the examination. Where it is impracticable to inspect specific areas then these may be excluded, by agreement.

**4.6.5.3.2** When no thermal post-processing is specified, volumetric NDE shall be performed on the component in the as printed condition provided the surface condition permits.

**4.6.5.3.3** Volumetric NDE inspection and calibration methods shall be in accordance with the applicable material specification and/or API product specification or product standard. The additive manufacturer shall consider indications specific to the process used (e.g., trapped powder in PBF) and specify an NDE method capable of detecting these indications.

**4.6.5.3.4** Volumetric NDE methods shall be in accordance with the applicable material specification and/or API product specification or product standard.

NOTE Where critical internal geometries and features cannot be inspected using traditional inspection methods, CT scanning or other comparable methods may be used.

#### 4.6.6 Critical Dimensional Inspection

Critical dimensions shall be specified and inspected.

The acceptance criteria shall be in accordance with relevant design and material specification as stated in the MPS and/or applicable API product specification or API product standard.

NOTE Where critical internal geometries and features cannot be inspected using traditional inspection methods, CT scanning or other comparable methods may be used to verify dimensional conformance.

### 4.7 Post-build Processing—First Article Component

Post-build processing for the first article component shall be in accordance with 6.6, and match that specified in the MPS.

### 4.8 Quality Control Requirements—Powder Bed Fusion (LB and EB)—First Article Inspection

Quality control requirements for the first article component manufactured by PBF (LB and EB) processes shall be in accordance with Table 2.

NOTE: 1 set = 3 test specimens.

**Table 2—Quality Control Requirements—Powder Bed Fusion (LB and EB)—First Article Inspection**

| | Parameter | AMSL 1 | AMSL 2 | AMSL 3 |
|---|---|---|---|---|
| Test Specimens | Chemical analysis (see 4.6.4.2) | Feedstock certificate only | 1 specimen/ build | 1 specimen/ build |
| | Tensile testing (see 4.6.4.3) | 1 specimen in 1 orientation (1 in Z) (1 total) | 1 specimen in 2 orientations (1 in Z and 1 at 90° to Z) (2 total) | 2 specimens at critical section height in Z orientation and 2 specimens at 90° to Z (4 total) |
| | Impact testing (see 4.6.4.4) | — | 1 set in the Z orientation, 1 set 90° degrees from Z | 1 set in the Z orientation, 1 set 90° degrees from Z |
| | Hardness testing (see 4.6.4.5) | — | 1 specimen/build with minimum 3 indents [a] | 1 specimen/build with minimum 3 indents [a] |

| | | | | |
|---|---|---|---|---|
| | Microstructure analysis (see 4.6.4.6) | — | 2 orientations (1 perpendicular to Z and 1 parallel to Z) | 2 orientations (1 perpendicular to Z and 1 parallel to Z) at the critical section height |
| | Density testing (see 4.6.4.7) | — | Required | Required |
| Component in the final condition | Visual inspection (see 4.6.5.1) | Required | Required | Required |
| | Volumetric NDE (see 4.6.5.3) | — | Required | Required |
| | Surface NDE (see 4.6.5.2) | Required | Required | Required |
| | Hardness testing (see 4.6.4.5) | Required | Required | Required |
| | Dimensional inspection (see 4.6.6) | Required | Required | Required |
| Integrated substrates | Visual inspection for cleanliness on base material (pre-build) (see 4.6.5.1) | Required | Required | Required |
| | Surface NDE on base material (pre-build) (see 4.6.5.2) | — | — | Required |
| [a] location and orientation by agreement | | | | |

## 4.9 Quality Control Requirements—Directed Energy Deposition (Blown Metal Powder)—First Article Inspection

Quality control requirements for the first article component manufactured by DED (blown metal powder) shall be in accordance with Table 3.

NOTE 1 For certain geometries, it could be necessary to perform the first article inspection described in Table 3 in multiple locations to obtain results that are representative of the entire component.

NOTE 2 1 set = 3 test specimens.

**Table 3—Quality Control Requirements—Directed Energy Deposition (Blown Metal Powder)—First Article Inspection**

| | Parameter | AMSL 1 | AMSL 2 | AMSL 3 |
|---|---|---|---|---|
| Test specimens | Chemical analysis (see 4.6.4.2) | Feedstock certificate only | 1 specimen/ build | 1 specimen/ build |
| | Tensile testing (see 4.6.4.3) | 1 specimen in 1 orientation (1 total) | 1 specimen in 2 orientations (1 in Z and 1 at 90° to Z) (2 total) | 3 specimens, orientations by agreement |
| | Impact testing (see 4.6.4.4) | — | 1 set in the Z orientation, 1 set 90° degrees from Z | 1 set in the Z orientation, 1 set 90° degrees from Z |
| | Hardness testing (see 4.6.4.5) | — | 1 specimen/build with minimum 3 indents [a] | 1 specimen/build with minimum 3 indents [a] |
| | Microstructure analysis (see 4.6.4.6) | — | Samples to be taken from the two planes that contain the Z axis and are perpendicular to each other | Samples to be taken from the two planes that contain the Z axis and are perpendicular to each other |
| | Density testing (see 4.6.4.7) | — | Required | Required |
| Component in the final condition | Visual inspection (see 4.6.5.1) | Required | Required | Required |
| | Volumetric NDE (see 4.6.5.3) | — | Required | Required |
| | Surface NDE (see 4.6.5.2) | Required | Required | Required |
| | Hardness testing (see 4.6.4.5) | Required | Required | Required |
| | Dimensional inspection (see 4.6.6) | Required | Required | Required |
| Integrated Substrates | Visual inspection for cleanliness on base material (pre-build) | Required | Required | Required |
| | Surface NDE on base material (pre-build) (see 4.6.5.2) | — | — | Required |
| | Interface cross-section tensile testing (see 4.6.4.3) | 1 specimen in 1 orientation (1 total) | 1 specimen in 2 orientations (1 in Z and 1 at 90° to Z) (2 total) | 3 specimens, orientations by agreement |
| | Interface cross-section impact testing (see 4.6.4.4) | — | 1 set in the Z orientation, 1 set 90° degrees from Z | 1 set in the Z orientation, 1 set 90° degrees from Z |

| | | | |
|---|---|---|---|
| Interface cross-section microstructure analysis (post-build) (see 4.6.4.6) | — | 1 orientation (perpendicular to fusion line along the primary deposition direction) | 2 orientations (perpendicular to fusion line) |
| Interface cross-section hardness testing (see 4.6.4.5) | — | 3 traverses 13 mm apart with 1 indent at 2 mm above fusion line, 1 indent at 1 mm below fusion line and 1 indent at 13 mm below fusion line | 3 traverses 13 mm apart with 1 indent at 2 mm above fusion line, 1 indent at 1 mm below fusion line and 1 indent at 13 mm below fusion line |
| Substrate tensile testing post-thermal processing (if thermal processing is applicable) (see 4.6.4.3) | 1 specimen in 1 orientation (1 total) | 1 specimen in 1 orientation (1 total) | 1 specimen in 2 orientations (2 total) |
| Substrate impact testing post-thermal processing (if thermal processing is applicable) (see 4.6.4.4) | — | 1 set in 1 orientation | 1 set in 2 orientations (2 total) |
| Substrate hardness testing post-thermal processing (if thermal processing is applicable) (see 4.6.4.5) | Required | Required | Required |
| Substrate microstructure analysis post-thermal processing (if thermal processing is applicable) (see 4.6.4.6) | — | 1 specimen in 1 orientation (1 total) | 1 specimen in 2 orientations (2 total) |

[a] location and orientation by agreement

## 4.10 Quality Control Requirements—Directed Energy Deposition (Wire)—First Article

Quality control requirements for the first article manufactured by DED-wire shall be in accordance with Table 4.

NOTE 1 For certain geometries, it could be necessary to perform the first article material tests described in Table 4 in multiple locations to obtain results that are representative of the entire component.

NOTE 2 set = 3 test specimens.

**Table 4—Quality Control Requirements—Directed Energy Deposition (Wire)—First Article Inspection**

| | Parameter | AMSL 1[a] | AMSL 2[b] | AMSL 3[c] |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Test specimens | Chemical analysis (see 4.6.4.2) | - | - | Required |
| | Tensile testing (see 4.6.4.3) | 1 specimen in the Z direction (1 total) | - | 3 specimens, orientations by agreement |
| | Impact testing (see 4.6.4.4) | - | - | 1 set in the Z orientation, 1 set 90° degrees from Z |
| | Hardness testing (see 4.6.4.5) | - | - | Required |
| | Microstructure analysis (see 4.6.4.6) | - | - | Samples to be taken from the two planes that contain the Z axis and are perpendicular to each other |
| Component in the final condition | Visual inspection (see 4.6.5.1) | Required | Required | Required |
| | Volumetric NDE (see 4.6.5.3) | - | - | Required |
| | Surface NDE (see 4.6.5.2) | - | - | Required |
| | Hardness testing (see 4.6.4.5) | - | - | Required |
| | Dimensional inspection (see 4.6.6) | - | - | Required |
| Integrated Substrates | Visual inspection for cleanliness on base material (pre-build) | - | - | Required |
| | Surface NDE on base material (pre-build) (see 4.6.5.2) | - | - | Required |
| | Interface cross-section tensile testing (see 4.6.4.3) | - | - | 3 specimens, orientations by agreement |
| | Interface cross-section impact testing (see 4.6.4.4) | - | - | 1 set in the Z orientation, 1 set 90° degrees from Z |
| | Interface cross-section microstructure analysis (post-build) (see 4.6.4.6) | - | - | 2 orientations (perpendicular to fusion line) |
| | Interface cross-section hardness testing (see 4.6.4.5) | - | - | 3 traverses 13 mm apart with 1 indent at 2 mm above fusion line, 1 indent at 1 mm below fusion line and 1 |

| | | | | |
|---|---|---|---|---|
| | | | | indent at 13 mm below fusion line |
| | Substrate tensile testing post-thermal processing (if thermal processing is applicable) (see 4.6.4.3) | - | - | 1 specimen in 2 orientations (2 total) |
| | Substrate impact testing post-thermal processing (if thermal processing is applicable) (see 4.6.4.4) | - | - | 1 set in 2 orientations (2 total) |
| | Substrate hardness testing post-thermal processing (if thermal processing is applicable) (see 4.6.4.5) | - | - | Required |
| | Substrate microstructure analysis post-thermal processing (if thermal processing is applicable) (see 4.6.4.6) | - | - | 1 specimen in 2 orientations (2 total) |

[a] AMSL 1 qualification is performed in accordance with Section 4.6.3.1 (i.e. the first article testing shall use a qualified weld procedure, and additional testing shall be performed as specified in Table 3).

[b] AMSL 2 qualification is performed in accordance with Section 4.6.3.1 (i.e. the first article testing shall use a qualified welding procedure as defined in Section 5.2, additional testing shall be performed as specified in Table 3).

c AMSL 3 qualification is performed in accordance with Section 4.6.3.2 (i.e. first article testing shall use a qualified welding procedure as defined in Section 5.2 and additional testing shall be performed as specified in Table 3).

## 4.11 Quality Control Requirements—Binder Jetting—First Article Inspection

Quality control requirements for the first article component manufactured by the BJT process shall be in accordance with Table 5.

**Table 5—Quality Control Requirements—Binder Jetting First Article Inspection**

| | Parameter | AMSL 1 | AMSL 2 | AMSL 3 |
|---|---|---|---|---|
| Test specimens | Chemical analysis (see 4.6.4.2) | 1 specimen/ build | 1 specimen/ build | 1 specimen/ build |
| | Tensile testing (see 4.6.4.3) [a] | 1 specimen in 1 orientation (1 total) | 1 specimen in 2 orientations (1 in Z and 1 at 90° to Z) (2 total) | 3 specimens, orientations by agreement |

| | | | | |
|---|---|---|---|---|
| | Impact testing (see 4.6.4.4) [a] | — | 1 set in the Z orientation, 1 set 90° degrees from Z | 1 set in the Z orientation, 1 set 90° degrees from Z |
| | Hardness testing (see 4.6.4.5) | 1 specimen/build with minimum 3 indents [b] | 1 specimen/build with minimum 3 indents [b] | 1 specimen/build with minimum 3 indents [b] |
| | Microstructure analysis (see 4.6.4.6) | Required | Required | Required |
| | Density testing (see 4.6.4.7) | Required | Required | Required |
| Component in the final condition | Visual inspection (see 4.6.5.1) | Required | Required | Required |
| | Volumetric NDE (see 4.6.5.3) | Required | Required | Required |
| | Surface NDE (see 4.6.5.2) | Required | Required | Required |
| | Hardness testing (see 4.6.4.5) | Required | Required | Required |
| | Dimensional inspection (see 4.6.6) | Required | Required | Required |

[a] Tensile and impact testing are not required for hard metals; see Annex C for guidance.

[b] location and orientation by agreement

## 5 Limits on the Qualification of the Additive Manufacturing Process

### 5.1 General

#### 5.1.1 Essential Variables

Additive manufacturing process variables shall be controlled and reported to the purchaser as indicated in 5.2 and 5.3.

Any change to limits or ranges of essential variables listed in Table 6 through Table 8 from the originally qualified additive manufacturing process requires requalification of the additive manufacturing process unless the requirements of 5.1.2 are met.

The requalification shall use the new values for the affected variables and the results shall be documented. The requirements of the requalification shall be as specified for the applicable AMSL in Section 4.

#### 5.1.2 Requalification Exceptions

Changes to the limits and ranges of essential variables within the previously qualified limit/range shall be documented by the additive manufacturer, including their impact on the finished component(s) and on the other essential variables listed in Table 6 through Table 8. In case there is no impact, by agreement, no requalification is required.

In case of an impact on the finished component(s) and/or on the other essential variables listed in Table 6 through Table 8, a requalification in accordance with 5.1.2 may be omitted by agreement.

## 5.2 Essential Additive Manufacturing Variables

**5.2.1** Table 6 through Table 8 define the additive manufacturing essential variables for each process. Each essential variable has an applicable AMSL and a Purchaser reporting requirement. For all changes to essential variables the first article component shall be requalified in accordance with Section 4.If the applicable AMSL is not listed for the relevant essential variable, the variable is not considered essential for that specific AMSL. The additive manufacturer shall have a written procedure for defining digital product definition (DPD) file, such as number, date, or tracking number, to confirm that non-reported variables have been locked in and not changed since the original qualification.

For PBF and DED-Blown Powder, Table 6 defines the essential additive manufacturing variables.

For BJT, Table 6 defines the essential additive manufacturing variables.

**5.2.2** For DED-Wire, Table 7 defines the essential additive manufacturing variables. For DED-Wire processes, AMSL 1, when the procedure is not qualified to ASME Section IX Article VI, all variables required by Article VI shall be recorded. Other DED-Wire processes not approved within ASME Section IX Article VI may be accepted by agreement and should be qualified using the ASME Section IX Article VI qualification methodology and relevant essential variables.

**5.2.3** For DED-wire if interlayer temperature measurement or oscillation greater than 12 mm is used, the thickness qualified shall be limited to the thickness range of the qualification coupon(s). For AMSL 2 and AMSL 3, the DED-Wire process shall utilize a qualified welding procedure per the requirements of ASME Section IX Article VI with the additional essential variables shown in Table 7. If the procedure qualification includes a PWHT that relies on rapid cooling across the entire thickness, the component printed thickness shall be limited to the thickness range of the bracketed qualification coupon(s).

NOTE DED-Wire components with an integrated substrate, the Purchaser may define a more restrictive integrated substrate designation (type, specification, grade) beyond the requirements of ASME IX Article VI.

**Table 6—PBF (LB and EB) and DED-Blown Powder Essential Additive Manufacturing Variables**

| Essential Variable | PBF (LB and EB) | | DED - Blown Powder | |
|---|---|---|---|---|
| | Applicable AMSL | To Be Reported | Applicable AMSL | To Be Reported |
| Specified feedstock chemistry | 1, 2, 3 | Y | 1, 2, 3 | Y |

| | | | | |
|---|---|---|---|---|
| Specified powder morphology, flowability, and particle size distribution | 2, 3 | Y | 2, 3 | Y |
| Specified post-processing heat treatment and other thermal processes | 1, 2, 3 | Y | 1, 2, 3 | Y |
| Specified shield gas specification | 1, 2, 3 | Y | 1, 2, 3 | Y |
| AM machine manufacturer and machine system / identifier | 1, 2, 3 | Y | 1, 2, 3 | Y |
| Name and revision number of the DPD | 1, 2, 3 | Y | 1, 2, 3 | Y |
| Build platform material | 1, 2, 3 | Y | 1, 2, 3 | Y |
| AM machine unique ID | 3 | Y | - | - |
| Feedstock storage variables | 1, 2, 3 | N | 1, 2, 3 | N |
| Specified humidity of chamber atmosphere[a] (LPBF) or shield gas[b] | 1, 2, 3 | N | 1, 2, 3 | N |
| Oxygen and vacuum setpoint and min/max permitted values during operation | 1, 2, 3 | N | 1, 2, 3 | N |
| Build platform specified minimum thickness | 1, 2, 3 | N | 1, 2, 3 | N |
| AM machine physical location | 1, 2, 3 requalification by agreement | N | 1, 2, 3 requalification by agreement | N |
| AM machine software/firmware version (see 4.2.3) | 1, 2, 3 | N | 1, 2, 3 | N |
| Powder production method | 1, 2, 3 | N | 1, 2, 3 | N |
| Powder manufacturer | 2, 3 | N | 2, 3 | N |
| Modifications to shield gas flow hardware configuration | 1, 2, 3 | N | 1, 2, 3 | N |
| Programmed layer height | 1, 2, 3 | N | 1, 2, 3 | N |
| Modifications to the recoater hardware configuration | 1, 2, 3 | N | - | - |
| modifications to the energy delivery system[c] | 1, 2, 3 | N | 1, 2, 3 | N |
| Build platform preheat temperature | 1, 2, 3 | N | 1, 2, 3 | N |
| Interpass temperature range | - | N | 1, 2, 3 | N |

[a] For printing equipment that cannot assess the humidity of the chamber, the humidity of the printing equipment room shall instead be treated as an essential variable.

[b] Including carrier gas flow rate and shield gas flow rate

[c] Including changing of the energy source's maximum power rating (e.g., 200 watts to 400 watts or 1 KW to 6–8 KW and vice versa), change in laser focus, laser spot size, change of energy source type and OEM (e.g., from ytterbium fiber to diode lasers or CO2 laser), change of scanner, F theta lens, nozzle type (coaxial, multistream, wide track for powders), and/or increasing or decreasing number of lasers

**Table 7—BJT Essential Additive Manufacturing Variables**

| Essential Variable | BJT | |
|---|---|---|
| | Applicable AMSL | To Be Reported |
| Specified feedstock chemistry | 1, 2, 3 | Y |

| | | |
|---|---|---|
| Specified powder morphology, flowability, and particle size distribution | 2, 3 | Y |
| Binder (trade/grade) name | 1, 2, 3 | Y |
| Specified post-processing heat treatment and HIP | 1, 2, 3 | Y |
| AM machine manufacturer and machine / system identifier | 1, 2, 3 | Y |
| Name and revision number of the DPD | 1, 2, 3 | Y |
| AM machine unique ID | 3 | Y |
| Feedstock storage variables | 1, 2, 3 | N |
| Binder Composition | 1, 2, 3 | N |
| Sintering Process | 1, 2, 3 | N |
| AM machine physical location | 1, 2, 3 requalification by agreement | N |
| AM machine software/firmware version (see 4.2.3) | 1, 2, 3 | N |
| Powder production method | 1, 2, 3 | N |
| Powder manufacturer | 2, 3 | N |
| Programmed layer height | 1, 2, 3 | N |
| Modifications to the energy delivery system | 1, 2, 3 | N |
| Modifications to the print head configuration | 1, 2, 3 | N |

**Table 8—DED-Wire Essential Additive Manufacturing Variables**

| Essential Variable | DED - Wire | |
|---|---|---|
| | Applicable AMSL | To Be Reported |
| All ASME IX Article VI Essential Variables | 1, 2, 3 | Y |
| Name and revision number of the DPD | 1, 2, 3 | Y |
| Modifications to the energy delivery system | 1, 2, 3 | N |
| AM machine software/firmware version (see 4.2.3) | 1, 2, 3 | N |
| Temperature Measurement Method (inter-bead or inter-layer) | 1, 2, 3 | Y |
| Use of oscillation | 1, 2, 3 | Y |
| NOTE For DPD's utilizing ASME IX QW 600 bracketed qualified procedures, the minimum preheat temperature is controlled by the limiting lower interpass temperature. | | |



# 6 Components Production Control

## 6.1 General

Once the additive manufacturing process is qualified in accordance with Section 4, the production of additively manufactured metallic components shall conform to the requirements of Sections 6 and 7.

## 6.2 Manufacturing Process Specification

The additive manufacturer shall have a manufacturing process specification (MPS) that details the sequence of steps of the additive manufacturing process for each build or component(s) with the same:

a) applicable AMSL;
b) DPD file name and revision;
c) Feedstock material specification;
d) pre-build check (see 6.3);
e) post-processing activities, such as stress relieving, heat treatment, HIP, and machining;
f) quality control and inspection requirements (see Section 7);
g) documentation requirements (see Section 8);
h) heating and cooling strategy, when not included in the DPD (see 4.6.2).

Inspection and test plans shall be documented.

## 6.3 Pre-build Check

The additive manufacturer shall maintain a documented pre-build check procedure. As applicable, the procedure shall include verification of, at a minimum:

a) machine status, including maintenance, qualification, and calibration;
b) feedstock specification, expiration date, and quantity necessary to complete the build;
c) build platform or substrate;
d) shielding gas;
e) cleanliness of lenses;
f) recoater system;
g) feeder system;
h) build chamber cleanliness;
i) build chamber environment;
j) DPD file;
k) MPS or set of instructions in accordance with the MPS.

EXAMPLE 1 A pre-build check procedure for PBF for the feeder system may include: verification that the powder feeder, powder tank or bin, roller, blade, recoater, and overflow bin are functioning as intended.

EXAMPLE 2 A pre-build check procedure for DED for the feeder system may include: verification that the feedstock wire spool is free of knots/kinks or damage. Check the wire feeder motor and drive gears, carrier/shield gas flow rate, and that the feedstock carrying channels inside the nozzle are free from material buildup.

EXAMPLE 3 A pre-build check procedure for BJT for the feeder system may include: verification that the print head test pattern meets specification before printing (ensuring all jets are in line).

## 6.4 Batch Control and Powder Reuse

The additive manufacturer shall conform with the requirements of 4.3.4.

## 6.5 Process Interruptions

**6.5.1** The additive manufacturer shall maintain a documented procedure for the control of build interruptions and shall address both planned and unplanned interruptions.

**6.5.2** Resolution of unplanned interruption nonconformance reports shall be according to the applicable MPS.

**6.5.3** Planned build interruptions shall be performed in accordance with the applicable MPS.

**6.5.4** Records of build interruptions shall be maintained.

## 6.6 Post-build Processing

### 6.6.1 General

Post-build processing shall be performed in accordance with the applicable MPS. Post-build activities can include, but are not limited to, processes such as curing, de-powdering, sintering, stress relieving, heat treatment, hot isostatic pressing (HIP), and machining.

The temperature, hold times, component placement, and load size for the post-production processing for stress relief, mechanical properties, and microstructure shall be selected based on the specific requirements for the component, which may be different for the wrought and other variants of the same alloy.

NOTE Improperly heat-treat parameters may result in the formation of secondary phases deleterious to the properties and performance.

### 6.6.2 Stress Relief

All stress-relief operations shall be performed using equipment with verified maintenance and calibration records.

The additive manufacturer shall maintain a documented procedure for the stress-relieving process.

Stress-relieving operations shall be performed in accordance with the applicable design and material specifications as stated in the MPS.

### 6.6.3 Heat Treatment

**6.6.3.1** All heat treatment operations shall be performed using equipment with verified maintenance and calibration records.

**6.6.3.2** The additive manufacturer shall maintain a documented procedure for the heat treatment process(es).

**6.6.3.3** Time at temperature and details of thermal cycles shall conform with the material specifications for the specific materials used in the component build. Heat treatment furnaces shall be calibrated in accordance with the applicable product specification. When no product specification is specified, heat treatment furnaces shall be calibrated in accordance with API 6A.

### 6.6.4 Hot Isostatic Pressing (HIP)

**6.6.4.1** All HIP operations shall be performed using equipment with verified maintenance and calibration records.

**6.6.4.2** HIP operations shall be performed in accordance with the applicable design and material specifications as stated in the MPS.

**6.6.4.3** The additive manufacturer shall maintain a documented procedure for the control of the HIP process.

### 6.6.5 Curing, De-powdering, and De-binding/Sintering

Curing, de-powdering, and de-binding/sintering shall be performed using equipment with verified maintenance and calibration records.

The additive manufacturer shall maintain a documented procedure for the curing, de-powdering, and de-binding/sintering processes.

## 6.7 Marking and Identification of Production Components

All components shall be identified on associated records as follows:

a) “API 20S-1” for AMSL 1;
b) “API 20S-2” for AMSL 2;
c) “API 20S-3” for AMSL 3.

All components shall be serialized for traceability.

Specific part marking methods and marking locations shall be by agreement.

# 7 Production Component Quality Requirements

## 7.1 General

This section describes the inspection and testing requirements as defined in Table 10, Table 11, Table 12, and Table 13 for the production of additively manufactured metallic components, depending on the applicable AMSL. Orientations referred to in these tables are as defined in ISO/ASTM 52921.

**7.1.1** For PBF and BJT (all AMSLs), the destructive testing to assess the production component material properties shall be performed by using test specimens extracted and/or machined from prolongations or printed concurrently and co-located in the build with the component on the same build platform and subjected to the same thermal post-production processing.

**7.1.2** If concurrently printed specimens are to be used for an AMSL 3 PBF component, the gauge length of the specimen(s) in the Z-orientation and the planes of microstructure analysis shall encompass the Z-height of the critical section(s) of the component such as those identified by the stress distribution in the design documentation. If geometry limitations prevent specimens from being manufactured concurrently at the appropriate Z-height, the test specimen height shall be by agreement.

**7.1.3** For DED processes, a separate DPD(s) may be required to obtain test specimens for material testing in accordance with this section due to geometry limitations. Test specimens shall be representative of the production component. The MPS shall reference all DPDs used in the production build. When separate DPD(s) are used, test specimens shall be produced immediately before or after the production component(s).

**7.1.4** For BJT, the test specimen(s) shall be printed in the same build of the production component(s) and undergo the same post-build processing of 6.6, including curing, de-powdering, and sintering.

NOTE In some instances, it may be prudent to subject the test specimens not only to the thermal treatment, but to any additional post-fabrication steps imparted to the production component that could impact the material properties.

**7.1.5** Where sampling in Table 10, Table 11, Table 12, and Table 13 is specified, Table 9 shall apply. Samples selected from production lots shall be random. The acceptance number, as defined in ANSI/ASQ Z1.4, shall be zero.

**Table 9—Sampling**

| **Production Lot Size** | **Minimum Sample Size** |
|---|---|
| 1 to 8 | ALL |
| 9 to 50 | 8 |
| 51 to 90 | 13 |
| 91 to 150 | 20 |
| 151 to 280 | 32 |
| 281 to 500 | 50 |
| 501 to 1200 | 80 |
| Based on ANSI/ASQ Z1.4, Table 2, general inspection level II. | |

## 7.2 Control of Non-conforming Components

**7.2.1** The additive manufacturer shall establish and maintain documented procedures to ensure that components that do not conform to specified requirements are prevented from unintended use or installation.

These procedures shall provide for identification, documentation, evaluation, segregation (when applicable), notification of the purchaser, and disposition of non-conforming components.

**7.2.2** The additive manufacturer shall address non-conforming components in one or more of the following ways, in accordance with either API Q1 or ISO 9001:

a) repair with subsequent inspection to meet specified requirements (correction)
    a. rework with subsequent inspection to meet specified design and manufacturing requirements
b) release under concession;
c) scrap.

**7.2.3** For AMSL 2 and AMSL 3, the additive manufacturer shall notify the purchaser when non-conformances result in rework or repairs of components as illustrated in Figure 2.

**7.2.4** The additive manufacturer shall notify purchasers of non-conforming product(s) that has been released.

Any repair of additively manufactured components without purchaser approval is prohibited.

**7.2.5** Repaired and/or reworked components shall be inspected in accordance with documented specifications of the additive manufacturer.

**7.2.6** Where sampling is specified in Table 10, Table 11, Table 12, and Table 13, the following shall apply:

a) When inspecting or testing production lots, a sample that fails to meet the applicable requirements shall result in rejection of the entire lot, and the entire lot shall be re-inspected. The non-conforming component(s) shall be repaired or reworked with subsequent inspection to meet specified requirements (correction), released under concession, or scrapped.
b) In the case of rework, the reworked component(s) shall be re-inspected for the failed characteristic(s) and any characteristic(s) affected by rework.

Records of non-conforming components, as well as actions resulting from the disposition of components, shall be maintained.

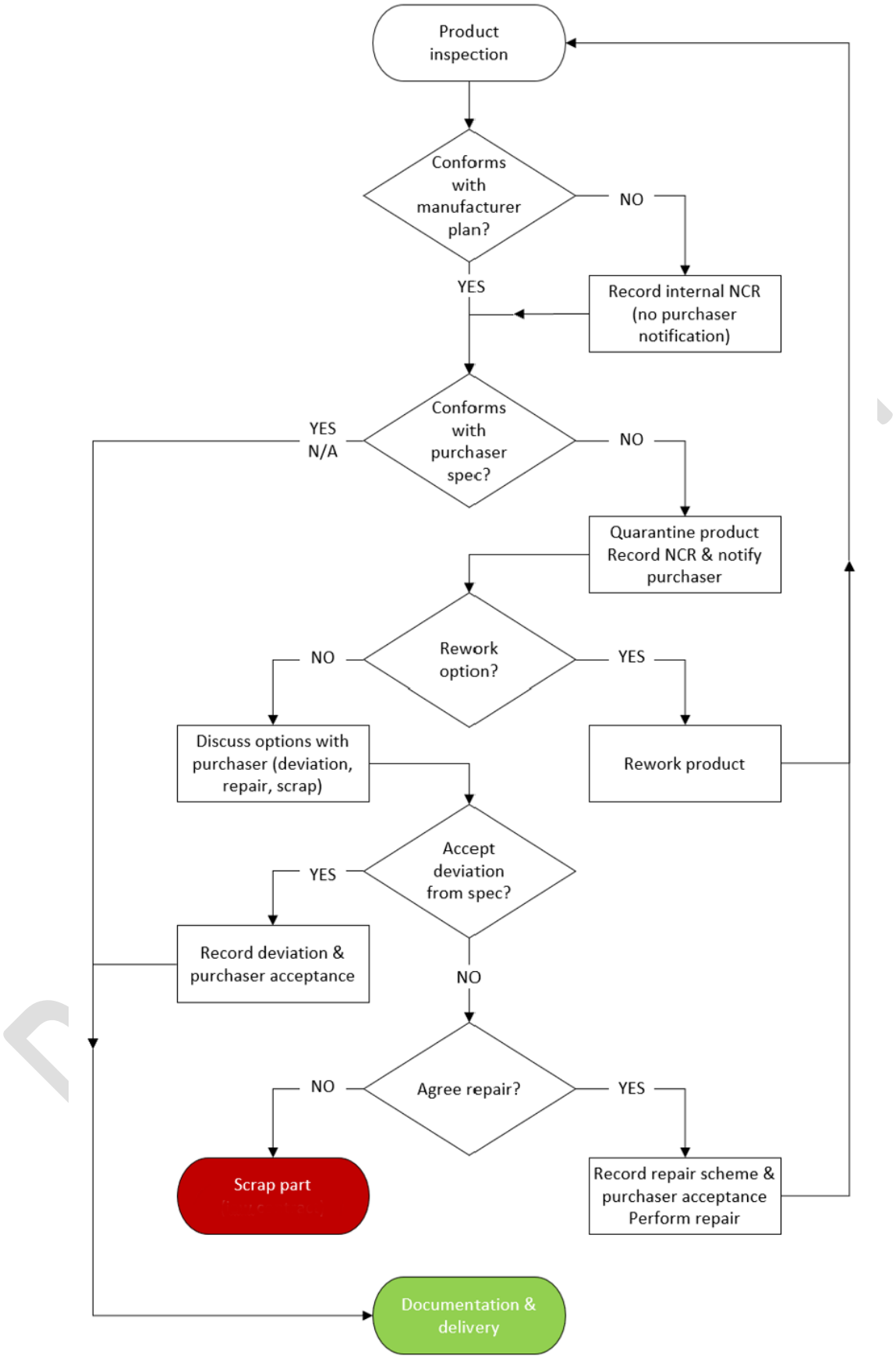

**Figure 2—Non-conformances Notification Flowchart**

### 7.3 Material Testing

Material testing shall be in accordance with 4.6.4.

### 7.4 Chemical Analysis

Chemical analysis shall be in accordance with 4.6.4.2.

### 7.5 Tensile Testing

Tensile testing shall be in accordance with 4.6.4.3.

### 7.6 Impact Testing

Impact testing shall be in accordance with 4.6.4.4.

### 7.7 Hardness Testing

Hardness testing shall be in accordance with 4.6.4.5.

### 7.8 Microstructure Analysis

Microstructure analysis shall be in accordance with 4.6.4.6.

### 7.9 Density Testing

Density testing shall be in accordance with 4.6.4.7.

### 7.10 Production Component Non-destructive Examination Requirement

#### 7.10.1 Visual Inspection

Visual inspection shall be in accordance with 4.6.5.1.

#### 7.10.2 Surface NDE

Surface NDE shall be in accordance with 4.6.5.2.

#### 7.10.3 Volumetric NDE

Volumetric NDE shall be in accordance with 4.6.5.3.

#### 7.10.4 Dimensional Inspection

Dimensional inspection shall be in accordance with 4.6.6.

#### 7.10.5 Quality Control Requirements—Powder Bed Fusion (LB and EB)—Production Components

Quality control requirements for production component(s) manufactured by powder bed fusion and EB processes shall be in accordance with Table 10.

**Table 10—Quality Control Requirements—Powder Bed Fusion (LB and EB)—Production Components**

| | Parameter | AMSL 1 | AMSL 2 | AMSL 3 |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Test specimens | Chemical analysis (see 7.4) | Feedstock certificate only | 1 specimen/ build | 1 specimen/ build |
| | Tensile testing (see 7.5) | 1 specimen in 1 orientation (1 in Z) (1 total) | 1 specimen in 2 orientations (1 in Z and 1 at 90° to Z) (2 total) | 2 specimens at critical cross section height in Z orientation and 2 specimens at 90° to Z (4 total) |
| | Impact testing (see 7.6) | — | 1 set in the Z orientation,<br>1 set 90° degrees from Z | 1 set in the Z orientation,<br>1 set 90° degrees from Z |
| | Hardness testing (see 7.7) | — | 1 specimen/build with minimum 3 indents [a] | 1 specimen/build with minimum 3 indents [a] |
| | Microstructure analysis (see 7.8) | — | 2 orientations (1 perpendicular to Z and 1 parallel to Z) | 2 orientations (1 perpendicular to Z and 1 parallel to Z) at the critical section height |
| | Density testing (see 7.9) | — | — | 1 specimen/build |
| Component in the final condition | Visual inspection (see 7.10.1) | All | All | All |
| | Volumetric NDE (see 7.10.3) | Sample | All | All |
| | Surface NDE (see 7.10.2) | Sample | All | All |
| | Hardness testing (see 7.7) | Sample | Sample | All |
| | Dimensional inspection (see 7.10.4) | Sample | Sample | All |
| Integrated substrates | Visual inspection for cleanliness on base material (pre-build) (see 7.10.1) | All | All | All |
| | Surface NDE on base material | — | — | All |

| | | | | |
|---|---|---|---|---|
| | (pre-build)<br>(see 7.10.2) | | | |
| [a]location and orientation by agreement | | | | |

### 7.10.6 Quality Control Requirements—Directed Energy Deposition (Blown Metal Powder)—Production Components

Quality control requirements for production component(s) manufactured by directed energy deposition (blown metal powder) shall be in accordance with Table 11.

NOTE For certain geometries, it could be necessary to perform the material tests described in Table 11 in multiple locations to obtain results that are representative of the entire component.

**Table 11—Quality Control Requirements—Directed Energy Deposition (Blown Metal Powder)—Production Components**

| | Parameter | AMSL 1 | AMSL 2 | AMSL 3 |
|---|---|---|---|---|
| Test Specimens | Chemical analysis<br>(see 7.4) | Feedstock certificate only | 1 specimen/ build | 1 specimen/ build |
| | Tensile testing<br>(see 7.5) | 1 specimen in 1 Z direction (1 total | 1 specimen in 2 orientations (1 in Z and 1 at 90° to Z) (2 total) | 3 specimens, orientations by agreement |
| | Impact testing<br>(see 7.6) | — | 1 set in the Z orientation, 1 set 90° degrees from Z | 1 set in the Z orientation, 1 set 90° degrees from Z |
| | Hardness testing<br>(see 7.7) | — | 1 specimen/build with minimum 3 indents [a] | 1 specimen/build with minimum 3 indents [a] |
| | Microstructure analysis<br>(see 7.8) | — | Samples to be taken from the two planes that contain the Z axis and are perpendicular to each other | Samples to be taken from the two planes that contain the Z axis and are perpendicular to each other |
| | Density testing<br>(see 7.9) | — | — | 1 specimen/build |
| Component in the final condition | Visual inspection<br>(see 7.10.1) | All | All | All |
| | Volumetric NDE<br>(see 7.10.3) | Sample | All | All |

| | | | | |
|---|---|---|---|---|
| | Surface NDE (see 7.10.2) | Sample | All | All |
| | Hardness testing (see 7.7) | Sample | Sample | All |
| | Dimensional inspection (see 7.10.4) | Sample | Sample | All |
| Integrated substrates | Visual inspection for cleanliness on base material (pre-build) (see 7.10.1) | All | All | All |
| | Surface NDE on base material (pre-build) (see 7.10.2) | — | — | All |
| | Interface visual inspection (post-build) (see 7.10.1) | All | All | All |
| | Interface cross-section microstructure analysis (post-build) (see 7.8) | — | — | All |
| | Interface cross-section tensile testing (post-build) (see 7.5) | — | — | All |
| [a]location and orientation by agreement | | | | |

### 7.10.7 Quality Control Requirements—Directed Energy Deposition (Wire)—Production Components

Quality control requirements for production component(s) manufactured by DED-Wire shall be in accordance with Table 12.

NOTE For certain geometries, it could be necessary to perform the material tests described in Table 12 in multiple locations to obtain results that are representative of the entire component.

**Table 12—Quality Control Requirements—Directed Energy Deposition (Wire)—Production Components**

| | Parameter | AMSL 1 | AMSL 2 | AMSL 3 |
|---|---|---|---|---|
| Test Specimens | Chemical analysis (see 7.4) | Feedstock certificate only | 1 specimen/ build | 1 specimen/ build |
| | Tensile testing (see 7.5) | 1 specimen in the Z direction (1 total) | 1 specimen in 2 orientations (1 in Z and 1 at 90° to Z) (2 total) | 3 specimens, orientations by agreement |
| | Impact testing (see 7.6) | — | 1 set in the Z orientation, 1 set 90° degrees from Z | 1 set in the Z orientation, 1 set 90° degrees from Z |
| | Hardness testing (see 7.7) | — | 1 specimen/build with minimum 3 indents [a] | 1 specimen/build with minimum 3 indents [a] |

| | | | | |
|---|---|---|---|---|
| | Microstructure analysis (se 7.8) | — | Samples to be taken from the two planes that contain the Z axis and are perpendicular to each other | Samples to be taken from the two planes that contain the Z axis and are perpendicular to each other |
| Component in the final condition | Visual inspection (see 7.10.1) | All | All | All |
| | Volumetric NDE (see 7.10.3) | — | All | All |
| | Surface NDE (see 7.10.2) | All | All | All |
| | Hardness testing (see 7.7) | - | All | All |
| | Dimensional inspection (see 7.10.4) | All | All | All |
| Integrated substrates | Visual inspection for cleanliness on base material (pre-build) (see 7.10.1) | All | All | All |
| | Surface NDE on base material (pre-build) (see 7.10.2) | — | — | All |
| | Interface visual inspection (post-build) (see 7.10.1) | All | All | All |
| | Interface cross-section microstructure analysis (post-build) (see 7.8) | — | — | All |
| | Interface cross-section tensile testing (post-build) (see 7.5) | — | — | All |
| [a] location and orientation by agreement | | | | |

### 7.10.8 Quality Control Requirements—Binder Jetting—Production Components

Quality control requirements for production component(s) manufactured by binder jetting shall be in accordance with Table 13.

**Table 13—Quality Control Requirements—Binder Jetting—Production Components**

| | Parameter | AMSL 1 | AMSL 2 | AMSL 3 |
|---|---|---|---|---|
| Test specimens | Chemical analysis (see 7.4) | 1 specimen/ build | 1 specimen/ build | 1 specimen/ build |
| | Tensile testing (as applicable) (see 7.5) [a] | 1 specimen in 1 orientation (1 total) | 1 specimen in 2 orientations (1 in Z and 1 at 90° to Z) (2 total) | 3 specimens, orientations by agreement |

| | | | | |
|---|---|---|---|---|
| | Impact testing (see 7.6) [a] | — | 1 set in the Z orientation, 1 set 90° degrees from Z | 1 set in the Z orientation, 1 set 90° degrees from Z |
| | Hardness testing (see 7.7) | 1 specimen/build with minimum 3 indents [b] | 1 specimen/build with minimum 3 indents [b] | 1 specimen/build with minimum 3 indents [b] |
| | Microstructure analysis (see 7.8) | All | 2 orientations (1 perpendicular to Z and 1 parallel to Z) | 2 orientations (1 perpendicular to Z and 1 parallel to Z) |
| Component in the final condition | Visual inspection (see 7.10.1) | All | All | All |
| | Volumetric NDE (see 7.10.3) | Sample | All | All |
| | Surface NDE (see 7.10.2) | Sample | All | All |
| | Density testing (see 7.9) | Sample | Sample | Sample |
| | Hardness testing (see 7.7) | Sample | Sample | All |
| | Dimensional inspection (see 7.10.4) | Sample | Sample | All |
| [a] Tensile and impact testing are not required for hard metals, see Annex C for guidance.<br>[b] location and orientation by agreement | | | | |

# 8 Documentation

## 8.1 General

The additive manufacturer shall establish and maintain documented procedures to control all documents and data required by this standard.

Documents and data may be in any type of media (hard copy or electronic) and shall be:

a) maintained to demonstrate conformance to specified requirements;
b) legible;
c) retained and readily retrievable;
d) stored in an environment to prevent damage, deterioration, or loss;
e) available and auditable.

## 8.2 Minimum Documentation and Retention

The documentation listed below shall be retained by the additive manufacturer for a minimum of 10 years following the date of manufacture:

a) additive manufacturing equipment location (site, room, building);
b) build/batch number;
c) printer model;
d) additive manufacturing equipment firmware and software versions;
e) MPS;
f) records of feedstock as defined in Section 4;
g) DPD file as defined in Section 4;
h) for binder jetting: scaling strategy;
i) for DED-Wire: Production records to demonstrate that the production component was produced in accordance to the qualified ASME IX Article VI procedure(s);
j) thermal post-processing times, temperatures, and cooling media;
k) for HIP processing: standard for the gas used, pressure, temperature, dwell time, and cooling rate;
l) test records, including records of the examinations (NDE), mechanical testing, and metallographic evaluations, as described in Section 7;
m) other documents provided with the component(s) as outlined in 8.3.

NOTE Purchaser or regulatory requirements may specify a longer record retention period.

### 8.3 Documentation Provided with the Component(s)

At a minimum, the following documentation shall be supplied in conformance with EN 10204, type 3.1 by the additive manufacturer for each component:

a) Essential variables in accordance with Section 5.2;
b) certificate of conformance;
c) MPS;
d) test results, including records of the examinations (NDE), mechanical testing, and metallographic evaluations, as described in Section 7;
e) deviations from governing design and/or construction specifications/standards;
f) a record of all repairs or rework.

The purchaser can specify supplemental documentation requirements in accordance with Annex B.

## 9 Handling, Storage, and Shipping

Components shall be packaged for storage or transit in accordance with the written specifications of the additive manufacturer or as otherwise specified by the purchaser.

# Annex A

(informative)

# Non-essential Additive Manufacturing Variables Guidance

## A.1 Non-essential Additive Manufacturing Variables

Table A.1 is intended as guidance for non-essential additive manufacturing variables, and changes to these parameters do not require a requalification.

**Table A.1—Non-essential Additive Manufacturing Variables**

| Parameter |
|---|
| Cleaning procedures for ancillary equipment (for example, sieves, hand tools, power tools, powder storage containers, powder transport systems, and delivery mechanism to machine) |
| Replacement in kind of recoater arm and/or motor |
| Method of CAD file transfer to machine |
| Laser field alignment maintenance procedures[a] |
| Machine room temperature and humidity |
| Facility cleanliness practices |
| Minimum layer time/process pause[b] |
| Gas recycling flow speed (or equivalent)[b] |
| Chamber pressure[b] |
| Recoating speed[b] |

[a] As an example, ISO/ASTM 52941 provides guidance on acceptance tests for PBF-LB equipment.

[b] This parameter may be unavailable if the printing equipment is not equipped to measure it.

# Annex B

(informative)

# Supplemental Documentation Requirements

The purchaser may request supplemental documentation at the time of order placement. An exemplar list of items that may be requested is shown below:

a) calibration records (purchaser to identify requirements for equipment when ordering);
b) current quality management system certificate;
c) print location (site, room, building);
d) build/batch number;
e) planned and unplanned print interruption records;
f) records of feedstock as defined in Section 4;
g) printing equipment maintenance records;
h) NDE personnel qualification records;
i) NDE procedures;
j) operator's training records.

# Annex C

(informative)

# Supplemental Material Test Guidance for Hard Metal Components Manufactured with Binder Jetting

## C.1 General

The material tests described in Section 4 and Section 8 may not be adequate for components made of certain materials (e.g., hard metals) manufactured with BJT. For such materials, the purchaser may select supplemental material tests from this annex at time of order placement. Table C.1 is for guidance; additional tests may be performed by agreement.

EXAMPLE Tensile testing is normally not adequate for low-ductility materials; therefore, the transverse rupture strength test from C.2 may be used.

## C.2 Supplemental Material Test Guidance for Hard Metal Components Manufactured with Binder Jetting

For hard metal components manufactured with binder jetting, supplemental material tests may be required in order to evaluate the component. Guidance for additional material tests is shown in Table C.1; other tests may be performed, by agreement.

**Table C.1—Supplemental Material Test Guidance for Hard Metals Components Manufactured with Binder Jetting**

| Mechanical Testing | Wear Testing | Physical Property Testing |
|---|---|---|
| Transverse rupture strength (ASTM B406) | Abrasive wear (ASTM G65 or ASTM B611) | Thermal diffusivity (ASTM E1461) |
| Palmqvist toughness (ISO 28079) | — | Thermal expansion (ASTM E228) |
| Fracture toughness (ASTM B771) | — | — |
| Compressive strength (ASTM E9) | — | — |

Acceptance criteria shall be in accordance with the relevant design and material standards as stated in the MPS or applicable product specification.

# ANNEX D
# Non-Destructive Criteria Guideline
# (Informative)

## D.1 Background and Scope

This informative Annex provides supplemental information regarding the application of AMSL levels to inspection and provides examples of acceptance criteria. The inspection and acceptance information concentrates on non-destructive testing.

The annex is organized as follows:

a) Assessing product to determine inspection requirements;
b) Inspection detail resources (external resources);
c) Initial qualification including First Article versus ongoing production inspection/testing;
d) Examples of applications with associated acceptance criteria.

AM is an evolving technology, and the use of established and new non-destructive techniques should be considered and approached with the understanding that Annex D is informative and operable within the conditions as outlined by the non-destructive technique. Attention is recommended as additive manufacturing and its complexity is unique and non-destructive techniques and limitations should be well understood. There are cases where multiple NDE techniques are used in concert to better characterize the AM product and its potential defects.

## D.2 Component Assessment

An inspection plan includes but is not limited to physical measurements, surface and volumetric inspection, composition and microstructure, physical and mechanical properties. This Annex concentrates on post-process non-destructive inspection (used interchangeably with non-destructive testing (NDT)). Though not addressed in this Annex except by way of examples, there are other non-destructive means of evaluation such as functional tests, pressure tests, magnetic permeability etc.

Understanding the performance requirements of the AM component, and its importance to the function or reliability of the system involved is the first step in defining the inspection plan. The requirements and criticality are established by the AM component classification defined using documented methodologies and metrics including but not limited to the consequence of failure to people, environment, and resources. For example, the Product Specification Level (PSL), as defined in API 6A, are selected based on a quantitative risk analysis. A number of operating conditions are considered in the PSL selection, such as rated working pressure, general or sour service, etc.

NOTE 1 The inspection and testing requirements for first article and production components according to each AMSL are defined in Sections 4 and 7, respectively. The appropriate AMSL can be selected according to the AM component classification.

The NDT technique(s) applicable to the AM component classification are selected based on the geometrical complexity of the part and the types of imperfections to be detected, at a minimum.

The effects of design complexity, including features introduced to assist the build process and controlled in the digital product definition file, on NDT method selection are described in ASTM E3166–20, Section 5.5.6. The guidance for the inspection capabilities of conventional and novel NDT techniques according to the types of AM imperfections can be found in ASTM E3166–20, ISO/ASTM TR 52905:2023. Additive manufacturing introduces process-unique anomaly types potentially important to the component performance. Descriptions and classifications of AM imperfections and NDT techniques capable of detecting them are available in ASTM E3166–20, ISO/ASTM TR 52905:2023, and draft ISO/ASTM DIS 52948:2023.

NOTE 2 For existing designs that are previously manufactured using conventional methods, AM parts typically inherit the existing classification and associated inspection requirements. For components designed for AM, a combination of conventional and novel NDT techniques may be required.

The NDT acceptance criteria are defined according to the AM component classification. The acceptance criteria can be further refined between the critical cross-sections such as those identified by the stress distribution in the design documentation and the balance of the component.

The acceptance criteria for conventionally manufactured components as defined in the applicable design and construction codes or product specifications are normally based on the capabilities of the NDT techniques. Depending on the types of imperfections, they may only be used for reference for AM components. For highly critical AM components, the acceptance criteria may need to be established through correlation of performance and representative AM materials, for which dimensions of AM-unique flaws are quantitatively determined.

The capability of detecting the critical flaw size is verified during the procedure review according to the applicable NDT standards. For highly critical AM components and/or critical cross-sections, quantifiable verification using representative artifacts containing intentionally seeded AM flaws may be required. Fitness for service evaluations, such as those prescribed within industry codes like API 579-1/ ASME FFS-1 can help define critical flaws sizes. The probability of detection of the flaws in the context of the selected NDE method should also be considered.

NOTE 3 It is recommended that the inspectability is considered in the design for AM in order to increase the confidence of detection. Iterative verification during first article and initial production can be expected.

## D.3 Inspection Detail Resources

The defect classification & associated details continue to evolve. For example, the definition of and location of internal porosity. The user of this Annex should be aware of these changes.

### Table D.1 – API 20S Quality Control Requirements – Powder Bed Fusion (LB and EB)

| Inspection Parameter | First Article Inspection (Table 2) | | | | Production Inspection (Table 10) | | | |
|---|---|---|---|---|---|---|---|---|
| | Para. | AMSL 1 | AMSL 2 | AMSL 3 | Para. | AMSL 1 | AMSL 2 | AMSL 3 |
| Visual Inspection | 4.6.5.1 | Required | Required | Required | 7.10.1 | All | All | All |
| Surface NDE | 4.6.5.2 | Required | Required | Required | 7.10.2 | Sample | All | All |
| Volumetric NDE | 4.6.5.3 | — | Required | Required | 7.10.3 | Sample | All | All |
| Hardness Testing | 4.6.4.5 | Required | Required | Required | 7.7 | Sample | Sample | All |
| Critical Dimensional Inspection | 4.6.6 | Required | Required | Required | 7.10.4 | Sample | Sample | All |

NOTE the requirements listed in Table D.1 are those that are required by this document but the detailed requirements are not reproduced here and the user is referred back to the relevant paragraph(s) in the main body text.

### Table D.2 - Reference Specifications that can Assist in NDE Selection and Acceptance Criteria

| **Standard Number** | AWS D20.1: 2019 | NASA-STD-6030 2021-04-21 | PTB-13-2021 | DNV-ST-B203 2022-10 | ASTM E3166 - 20e1 | ISO/ASTM TR52905: 2023 | ASTM WK75329 | ISO/ASTM DIS 52948 | MIL-STD-1587F |
|---|---|---|---|---|---|---|---|---|---|
| **AM processes covered** | PBF DED | PBF (Laser) | PBF (Laser, EB) | PBF; DED; BJ | PBF; DED | PBF DED | PBF (Laser) | PBF | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Part classification** | Yes | Yes | - | Yes | - | - | - | - | Yes |
| **Imperfection classification** | - | - | - | - | Yes | Yes | Yes | Yes | |
| **Technique selection** | - | - | - | Yes | Yes | Yes | - | - | Yes |
| **Calibration, IQI, or AM artefacts** | - | Yes | - | - | Yes | Yes | - | - | Yes |
| **Inspection personnel** | Yes | - | - | Yes | Yes | Yes | - | - | |
| **Acceptance criteria** | Yes | - | - | Yes | - | Yes | Yes | - | |
| **Acceptance criteria by part classification** | Yes | Yes | - | Yes | - | - | Yes | - | Yes |
| **Inspection - Qualification** | Yes | Yes | Yes | Yes | - | - | - | - | |
| **Inspection - Production** | Yes | - | - | Yes | Yes | - | - | - | |

**Table D.3 - Acceptance Criteria Examples for NDE of Components**

| | Defect type | Acceptance Criteria | Notes | Reference |
|---|---|---|---|---|
| Surface Inspection | linear | no relevant indications | relevant ≥ 1.6mm | API 6A 21st ed. |
| | rounded | none greater than 5mm | | API 6A 21st ed. |
| | cracks | none permitted | levels 1&2 | ASTM wk75329 |
| | porosity | 1.5mm maximum single | levels 1&2 | ASTM wk75329 |
| | | cluster-3 pores > 2.5% mat. thickness | level 1 | ASTM wk75329 |
| | | cluster-7 pores > 2.5% mat. thickness | level 2 | ASTM wk75329 |
| | cracks | none permitted | classes A,B&C | AWS D20.1 2019 |
| | porosity | max dim. 0.25T or < 0.76mm | class A | AWS D20.1 2019 |
| | porosity | max dim. 0.33T or < 1.5mm | class B | AWS D20.1 2019 |
| | porosity | max dim. 0.5T or < 2.3 mm | class C | AWS D20.1 2019 |
| | | | | |
| Volumetric Inspection | cracks | no relevant permitted | relevant ≥ 1.6mm | API 6A 21st ed. |
| | indication | max length - 6.4 mm for T<19.0mm | PSL3 - RT | API 6A 21st ed. |
| | indication | max length - 6.4 mm for any T | PSL4 -RT | API 6A 21st ed. |
| | cracks | none permitted | levels 1&2 | ASTM wk75329 |

| | | | | |
|---|---|---|---|---|
| | voids & inclusions | 2.5% mat thickness longest dimension | level 1 | ASTM wk75329 |
| | | 1.5mm maximum single | level 2 | ASTM wk75329 |
| | | cluster - 3 pores > 2.5% mat. Thickness | level 1 | ASTM wk75329 |
| | cracks | none permitted | classes A,B&C | AWS D20.1 2019 |
| | porosity & inclusions | max dim. 0.33T or < 1.5mm | class A | AWS D20.1 2019 |
| | | max dim. 0.5T or < 2.3 mm | class B | AWS D20.1 2019 |

## D.4 Initial Qualification Including First Article Versus Ongoing Production Inspection/testing

Additive manufacturing is predominantly a digital process, which implies that that the digitally defined process characteristics can significantly affect the quality and integrity of the manufactured component. These process characteristics should be monitored and controlled using appropriate procedures in compliance with the requirements of the main document.

For Powder Bed Fusion (Laser Beam) process, detailed guidance is provided by ISO / ASTM 52930 regarding installation qualification (IQ), operational qualification (OQ), and performance qualification (PQ) of the equipment used for additive manufacturing. It helps to ensure that all key aspects of the primary / ancillary process equipment adhere to the AM equipment manufacturer's approved specification and that the determined process control limits produce a product that meets the design acceptance criteria.

For DED (GMAW), ASME IX (Article VI) provides a detailed guidance on the process used for determination of process control limits and qualification limits. However, to ensure that the product meets the design acceptance criteria, first article testing, and product testing is still required to be performed.

For Binder Jet (BJT), there are no suitable identified reference specifications that details qualification or production inspection/testing requirements.

The requirements of the first article and production testing are defined in the main document. This requires specific testing to be completed in compliance with the applicable inspection and test plan. The inspection and test plan needs to include type and frequency of NDT to be performed. This may change based on the agreed AMSL level for the component to be manufactured and needs to be agreed between the AM manufacturer and purchaser.

When a new or revised component is produced or if the production process used to make the component changes, it must be assessed and verified to ensure product realization processes can produce parts and assemblies that meet engineering and design requirements. The first article helps with assessing these requirements as routine end-product testing alone often is not sufficient to assure product quality. Also, limited end-product testing does not reveal all variations that can occur in the product and affect the safety and operational performance of the product.

Additionally, to ensure that the manufactured component is suitable for application, a fitness for service analysis may need to be completed. First article testing is the ideal opportunity for this analysis to ensure the suitability of the manufactured component for the required service conditions. API 579 can be used as a guide for such analysis as the design considerations and operating environmental conditions are well defined at this stage. The assessment can also help to define NDE acceptance criteria and the appropriate NDE technique can then be selected to perform the inspection. Such analysis may also highlight the need for additional testing that needs to be conducted to generate required materials properties specifically for additively manufactured materials. It

must be noted that the assessment of deposition strategy and effect of anisotropy should be considered prior to testing to ensure that the test data is representative of the manufactured component.

## D.5 EXAMPLES OF APPLICATIONS USING THIS ANNEX

The following examples illustrate the use of this informative Annex.

### Example 1: Application of Annex D – AMSL 1

Background and assessment of requirements including AMSL: The component in this example is a surface mounted valve module containing hydraulic fluid passages and electrical wire feed-throughs. The AM process is LPBF and the component material of construction is 316 stainless steel. Each build chamber yields 16 components plus test coupons for destuctive evaluation. The component surfaces are used as-printed except for the mounting section which is machined to maintain isolation between the passages and seals against a larger assembly. Each assembly utilizes several of these valve modules.

In evaluating the application it was determined that the module exhibits the following defining characteristics: (1) low stress levels; the differential pressure between the various chambers and channels in the module were very low. (2) the potential consequences of component failure were minor not resulting in failure of the greater assembly of which the module was a part. (3) The component is accessible and easily replaced if necessary.

The application was determined to be AMSL 1. The NDE required and detailed below conformed to API 20S (specifically Section 4.8).

In this example, a combination pressure test – component function test was performed for qualification on 100% of components at twice the operating pressure for the First Article.
In addition, a factory acceptance test (FAT) is performed that includes a pressure component function test.

| EXAMPLE 1 | | |
|---|---|---|
| Part Description | Surface mounted valve module containing hydraulic fluid passages and electrical wire feed-throughs. | |
| AMSL | 1 | |
| AMSL Assessment | In evaluating the application it was determined that the module exhibits the following defining characteristics: (1) low stress levels; the differential pressure between the various chambers and channels in the module were very low. (2) the potential consequences of component failure were minor not resulting in failure of the greater assembly of which the module was a part. (3) The component is accessible and easily repalced if necessary. | |
| Design Complexity | ASTM E3166-20e1, 5.5.6, Group 1 | |
| Component Material | 316 SS | |
| AM Process | PBF (LB). Each build chamber yields 16x parts plus test specimens. | |
| Post Process | Part surfaces are used as-printed except for the mounting section which is machined to maintain isolation between the passages and seals against a larger assembly. | |
| Final Condition | As-printed, except mounting sections are machined. | |
| Inspection category | 1st Article Qualification requirements | Production – ongoing requirements |
| Visual Inspection | All parts are visually inspected. Parts shall be uniform in color with no apparent cracks or other surface defects or abmormalites. | All parts are visually inspected. Parts shall be uniform in color with no apparent cracks or other surface defects or abmormalites. |
| Surface NDE | 100% INSPECTION using API 6A, Surface NDE – Non-ferromagnetic materials<br><br>Acceptance criteria for non-sealing surfaces are as follows:<br>- No relevant linear indication | Using tests and acceptance criteria for 1st Artcile Qualificatiion:<br>- Non-sealing surface NDE: one part from each build chamber |

| | | |
|---|---|---|
| | - No relevant rounded indication with a major dimension equal to or greater than 5 mm (3/16")<br>- Four or more relevantr rounded indications in a line separated by less than 1.6 mm (1/16") (edge to edge) are unacceptable<br><br>Acceptance criterion on machined sealing surfaces is as follows:<br>- No relevant indication equal to or greater than 0.8 mm (1/32")<br><br>A relevant indication is defined as one with a major dimension that is 1.6 mm (1/16") or greater on as-printed and as-machined non-sealing surfaces. A relevant indication is defined as one with a major dimension that is 0.8 mm (1/32") or greater on machined sealing surfaces | - Machined sealing surface NDE: all parts from each build chamber |
| Volumetric NDE | Three parts are randomly selected for first article inspection. Radiographic inspection is performed in accordance with ASTM E94 to a minimum equivalent sensitivity of 2% and a 2-2T quality level. The acceptance criteria are as follows:<br>- No cracks<br>- No elongated indication with a length greater than 1.6 mm (1/16")<br>- No evidence of build layer separation or lack of fusion<br><br>No volumetric NDE is required in production inspection. | N/A |
| Hardness Testing | One part hardness tested; 22 HRC maximum | One part hardness tested; 22 HRC maximum |
| Microstructure analysis | These attributes are not addressed in this informative annex | |
| Impact testing | | |
| Mechanical testing | | |
| Chemical analysis | | |
| Dimensional Inspection | Critical features of all parts from each build chamber. | Critical features of all parts from each build chamber. |
| Factory Acceptance Test | All parts shall be pressure function tested at 2x hydraulic fluid pressures. Valve component functions as designed with zero detected leakage during a 15 minute minimum hold period. | All parts function tested using standard hydraulic pressure |

**Example 2: Application of Annex D – AMSL 2**

Background and assessment of requirements including AMSL: The component is an actuator housing of an an hydraulic actuator that is used to operate a valve assembly. The near net shape of the actuator housing was deposited using DED Wire Arc AM process in low alloy steel. The yield strength of AM component will be equivalent to conventionally procured forged component. The component is machined on all surfaces post themal processing to allow surface NDE using Penetrant Inspection and volumetric inspection using Ultrasonic examination and conventional X-Ray inspection.

A detailed FMECA of the component intended application determined the criticality level to be AMSL 2 based on the following defining characteristics: (1) low stress levels – material yield strength utilisation is low (2) the potential consequence of component failure was low due to the availability of fail safe system inside the actuator assembly. (3) Potential loss of production due to well shutdown requirement for replacing the actuator assembly.

A complete API 6A functional test to demonstrate proper operation was performed for qualification component (1st Article) as per API 6A requirements. In addition, a factory acceptance test (FAT) is performed that includes a pressure test at 1.5 X rated working pressure.

| EXAMPLE 2 | |
|---|---|
| Part Description | Actuator Housing |
| AMSL | 2 |
| AM Testing Considerations | Testing to be performed on the prolongation and sacrificial component, deposited in the same build sequence.<br><br>Two step volumetric testing to be completed during manufacturig – UT post thermal processing and X-ray in finished machined condiion.<br><br>Additional tensile and charpy specimens distributed uniformly over the height of deposited volume on sacrificial component to demonstrate uniformity in mechanical properties.<br><br>Physical properties measurement to confirm design input parameters.<br>Corrosion testing in seawater + CP environment to ascertain design life for subsea use. |
| Component Material | ASTM A182 F22 |
| AM Process | DED (Wire Arc AM) |
| Post Process | Thermal post processing and machining. |
| Final Condition | Fully machined. |
| Visual Inspection | All parts are visually inspected. Parts shall be free from apparent cracks or other surface defects or abnormalites. |
| First Article Testing | All Items specified in API 20S and additional Tensile / Charpy specimens |
| Supplemental Testing | Physical properties measurement to confirm design input parameters.<br>Corrosion testing in seawater + CP environment to ascertain design life. |
| Production Testing | Two step volumetric testing to be completed during manufacturing – UT post thermal processing and X-ray in finished machined condition.<br>• Volumetric (UT) inspecion per ASME B&PV Code Sect. V Articles 4, 5<br>• RT per ASME B&PV Code Sect. V Article 2<br>• Liquid Penetrant inspection per ASME B&PV Code Sect. V Article 6 |
| Dimensional Inspection | Finish Machined state |
| Factory Acceptance Test | FAT to 1.5X Design Pressure. |

## Example 3: Application of Annex D – AMSL 3

| Part Description | Subsea Pipeline Buckle Arrestor, Flange Portion Printed onto Standard Linepipe |
|---|---|
| AMSL | 3 |
| AMSL Assessment | In evaluating the application it was determined that the module exhibits the following defining characteristics:<br>1. AM Portion is not considered pressure containing, only the pipe portion.<br>2. Design was optimized via FEA. |

| | |
|---|---|
| | 3. A duplicate sacrifical part was made for first article testing, including substrate testing<br>4. Component partially machined to provide UT compliant geometry prior to final machining.<br>5. CTOD testing was included as an additional suppliment |
| Design Complexity | ASME Section 8, Division 2 |
| Component Material | API 5L Grade Pipe and Equivalent Strengh AM Welding Consumable |
| AM Process | DED (WAAM) |
| Post Process | Part is to be heat treated and fully machined after printing. |
| Final Condition | Heat treated and the fully machined. |
| Visual Inspection | All parts are visually inspected. Parts shall be free from apparent cracks or other surface defects or abnormalites. |
| First Article Testing | All Items specified in API 20S, Table 3, AMSL 3 Column |
| Supplemental Testing | CTOD Testing |
| Production Testing | • Heat treated and then Volumetric (UT) inspecion per ASME Section 8, Division 1, Mandatory Appendix 12, in a semi-finished machined state with geometry compatible with UT inspection.<br>• Surface (MT) inspection per ASME Section 8, Division 1, Mandatory Appendix 6, in a finish machined state. |
| Dimensional Inspection | After Machining |
| Factory Acceptance Test | Buckle Arrestor is to pressure tested to 150% of Design Pressure. |

**Example 4: Application of Annex D – AMSL 3**

Background and assessment of requirements including AMSL: In evaluating the application it was determined that the part exhibits the following defining characteristics: (1) medium stress levels; (2) high operational risk as the component is not easily accessible for inspection and maintenance; (3) high production, environmental and human risk in the event of component failure.

The application was determined to be AMSL 3.

| | Method and Acceptance Criteria |
|---|---|
| Part Description | AM part contains free-form surfaces with internal channels or passages. |
| AMSL | 3 |
| AMSL Assessment | In evaluating the application, it was determined that the part exhibits the following defining characteristics:<br>1. medium stress levels;<br>2. high operational risk as the component is not easily accessible for inspection and maintenance;<br>3. high production, environmental and human risk in the event of component failure. |
| Component Material | 316L SS |
| AM Process | PBF (LB). Each build chamber yields 4x parts plus test specimens. |
| Post Process | Stress relief before separating from the build plate |
| Final Condition | As-printed, except sealing surfaces are machined. |
| Inspection category | First article qualification and production inspection have the same requirements. |
| Visual Inspection | All parts are visually inspected. Parts shall be uniform in color with no apparent cracks or other surface defects or abnormalities. |
| Surface NDE | Liquid penetrant inspects the machined sealing surfaces of all parts per API 6A, surface NDE, non-ferromagnetic materials. No relevant indication allowed. |

| | |
|---|---|
| Volumetric NDE | All parts are volumetrically inspected using computed tomography (CT). The inspection procedure shall be approved by certified ASNT (or equivalent) Level III personnel. The acceptance criteria are as follows:<br>- No trapped powder inside the channels<br>- No cracks, delaminations or other macroscopic anomalies<br>- No structural porosity i.e. surface close porosity and line or different agglomeration or pores<br>- No pores larger than 0.2 mm in diameter |
| Hardness Testing | One part from each build chamber is tested for hardness in accordance with ASTM E18/E10 on noncritical machined surfaces at 4x different locations. |
| Dimensional Inspection | Critical features of all parts from each build chamber. |
| Factory Acceptance Test | 100% of parts shall be pressure function tested at 2x hydraulic fluid pressures with zero detected leakage during a 15-minute minimum hold period. Changes of critical dimensions are recorded during test. |



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